Clear Air Turbulence (CAT) Simulation and Observation: Implications for Parameterization

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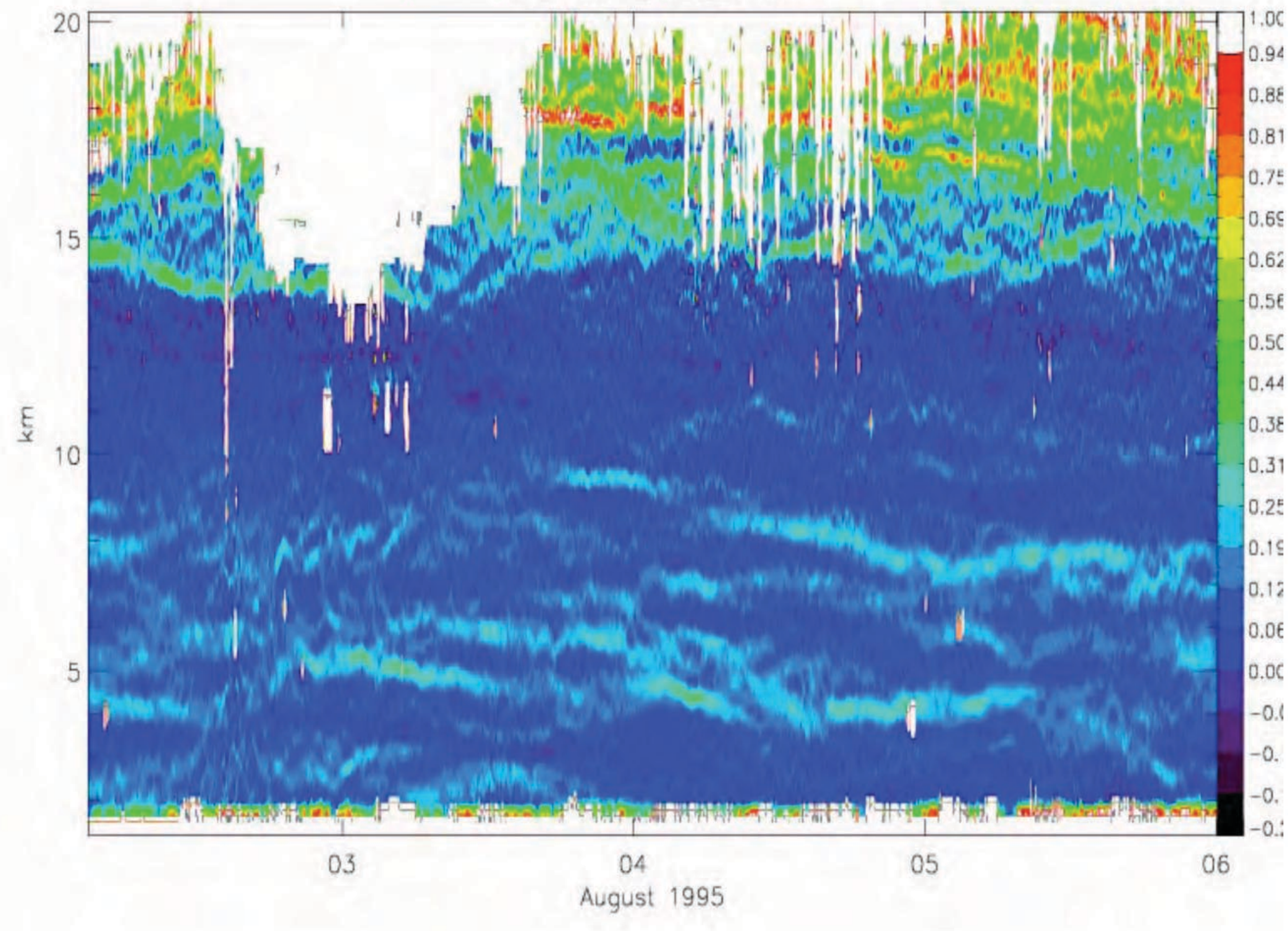
Observations of CAT layers with mu-rass in Japan

observation

Alexander, Tsuda, Furumoto, J. Atmos. Ocean. Tech. (2006)

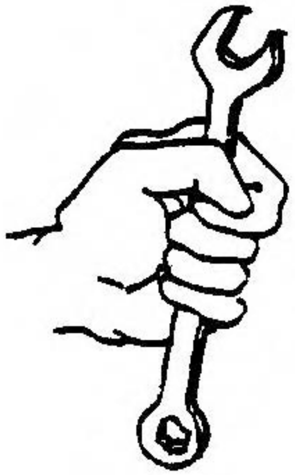


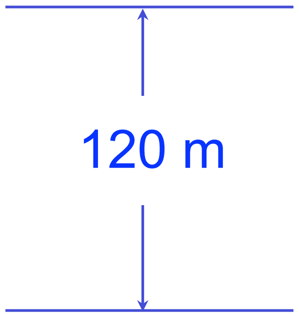
Example of turbulent layers observed with mu-rass in Japan. Layers range from 100-150m (resolution limit) up to 1km. Some layers persist over 4-day observing period and are seen to be rejuvenated on a diurnal time scale.

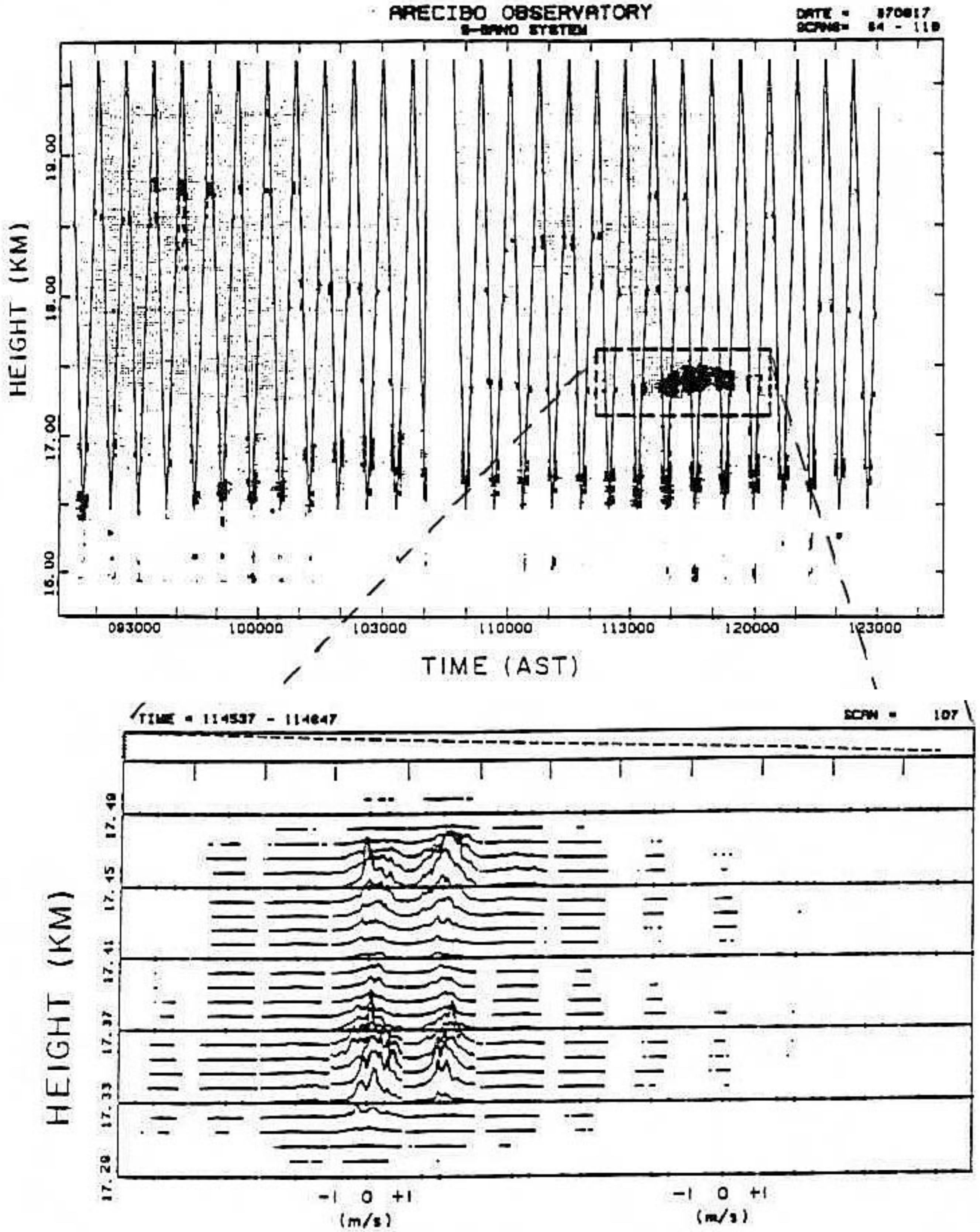
High-Resolution Radar Backscatter

Ierkic, Woodman & Perillat, Radio Science 25, 941 (1990)

$$Re = \frac{UL}{\nu} \approx 10^6 - 10^7$$

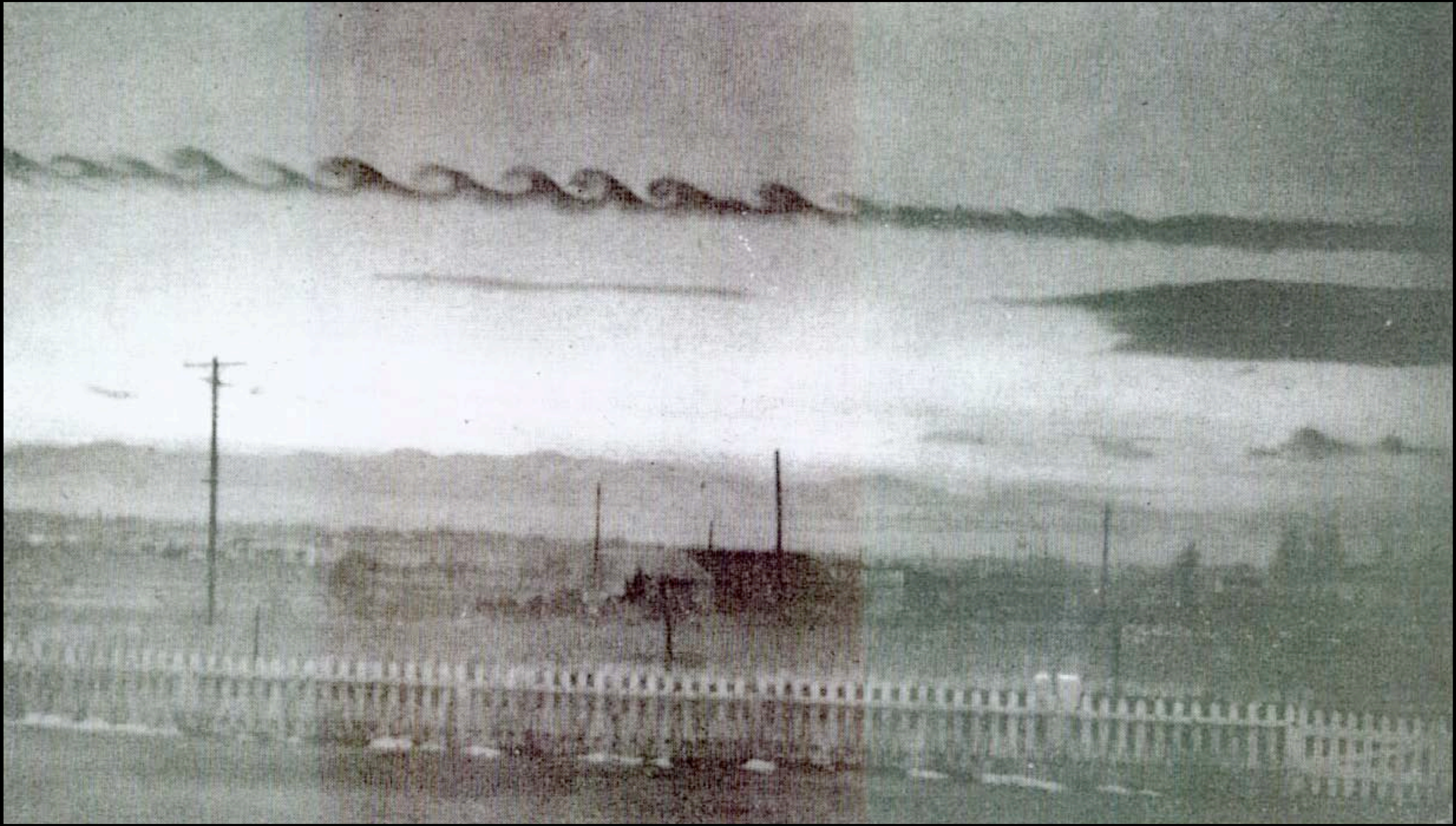






Estes Park, Colorado, 1979 (photo by Bob Perney)

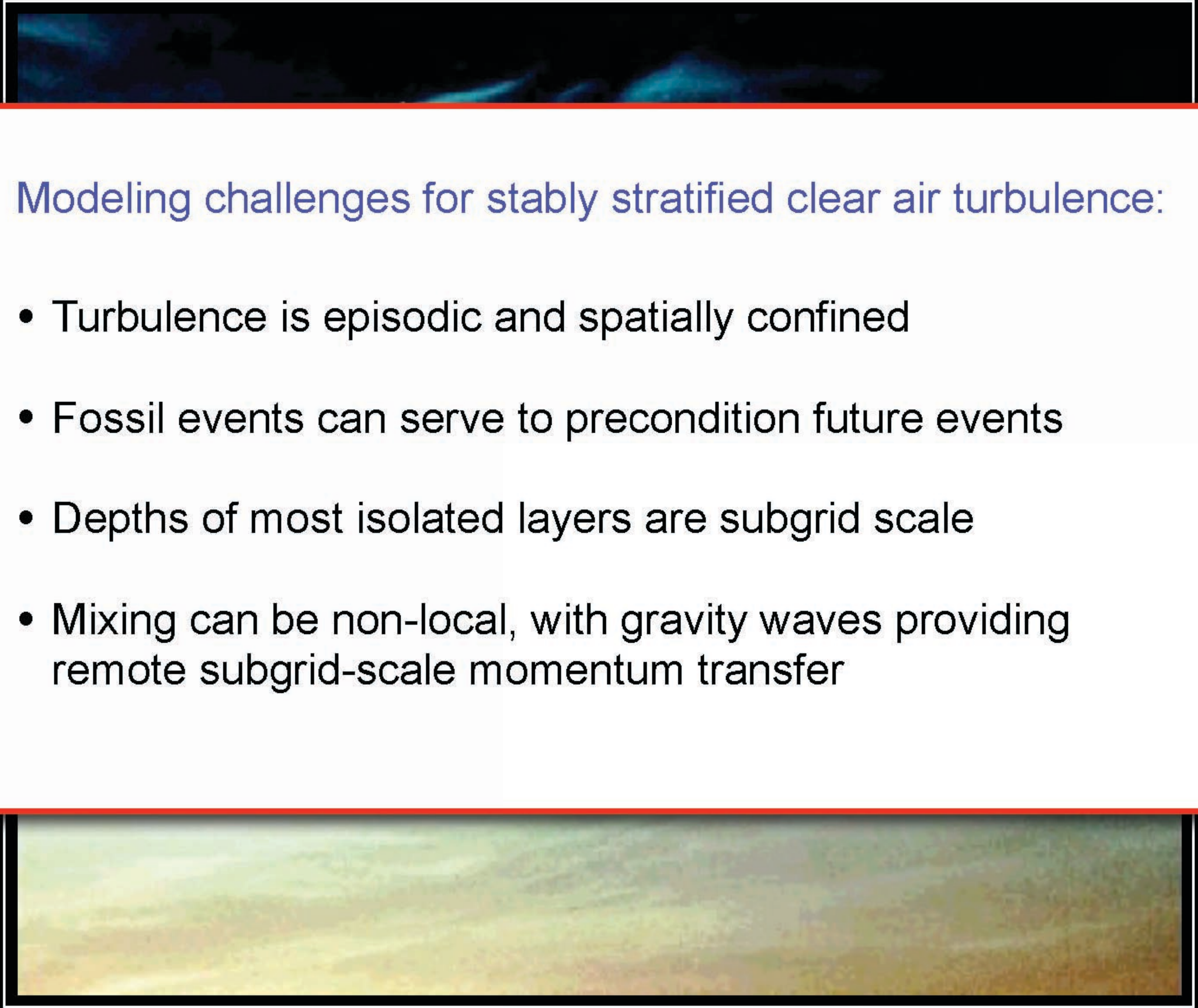
Colorado Springs, Colorado, 2000 (photo by Tye Parzybok)



Denver, Colorado, 1953 (photo by Paul E. Branstine)

Lafayette, Colorado, 2002 (photo by Joe Werne)

Noctilucent Clouds, Kustavi, Finland, 1989 (photo by Pekka Parviainen)



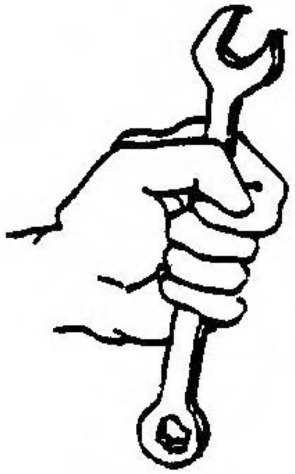
Modeling challenges for stably stratified clear air turbulence:

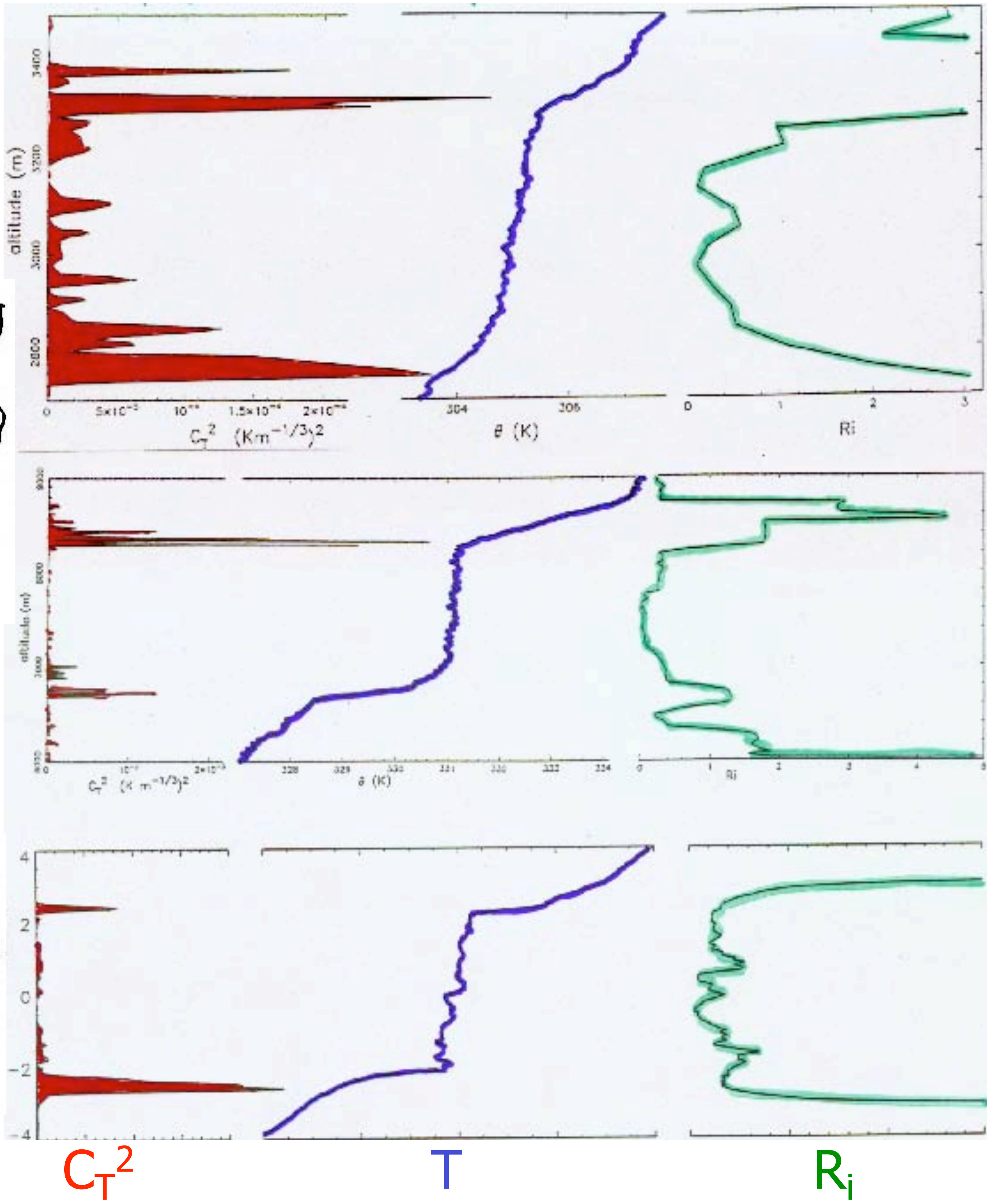
- Turbulence is episodic and spatially confined
- Fossil events can serve to precondition future events
- Depths of most isolated layers are subgrid scale
- Mixing can be non-local, with gravity waves providing remote subgrid-scale momentum transfer

Noctilucent Clouds, Kustavi, Finland, 1989 (photo by Pekka Parviainen)

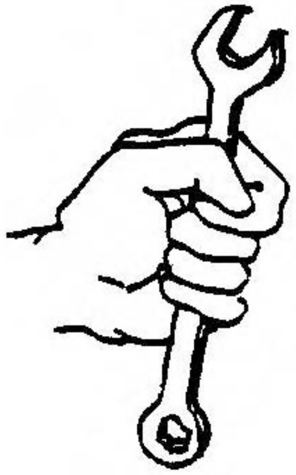
CAT layers: What are their signatures?

Coulman, Vernin & Fuchs, Applied Optics <u>34</u> 5461 (1995)

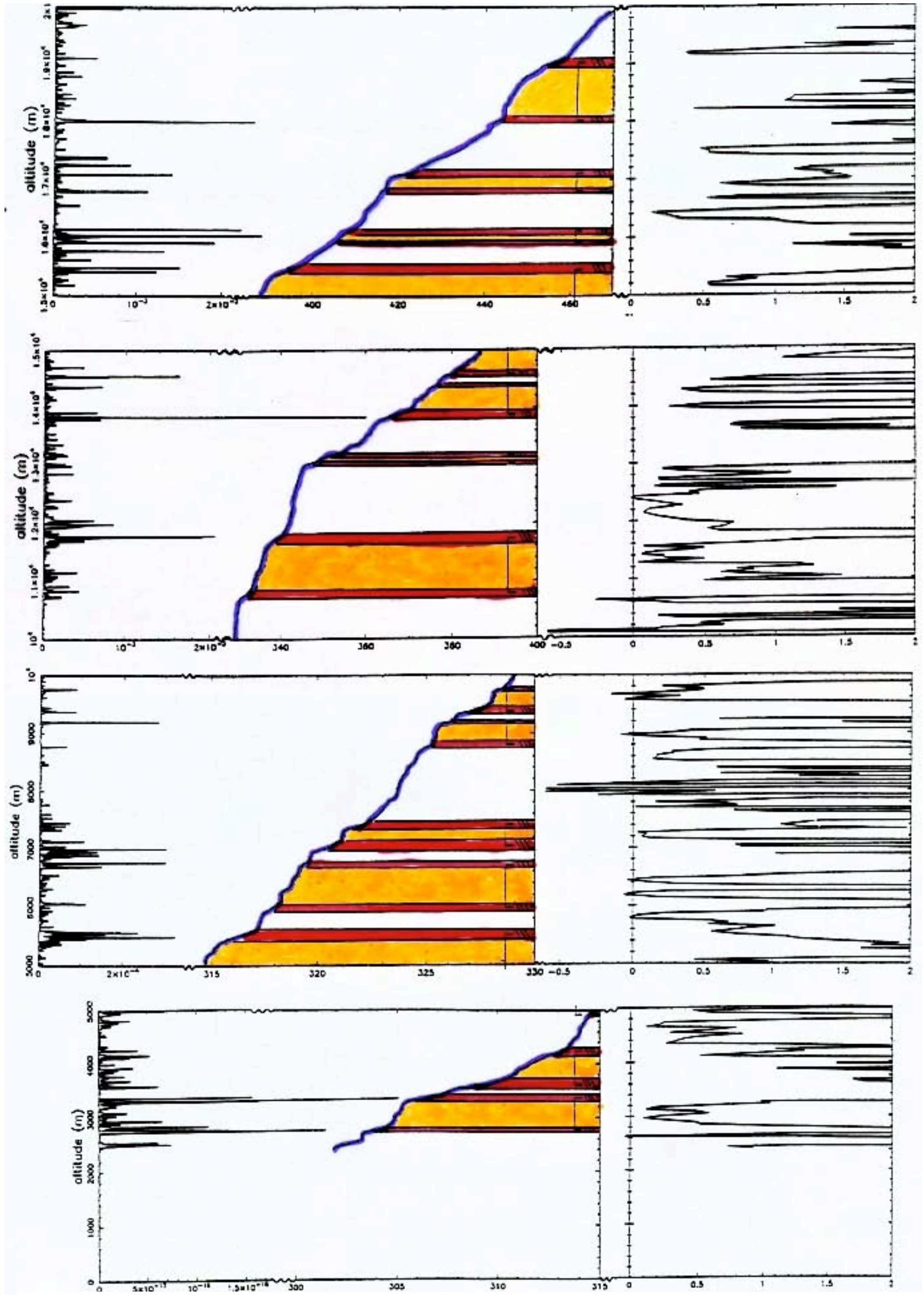




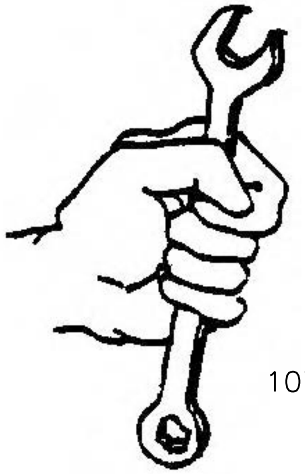
CAT layers: How typical or rare are they?



Coulman, Vernin & Fuchs, Applied Optics 34 5461 (1995)

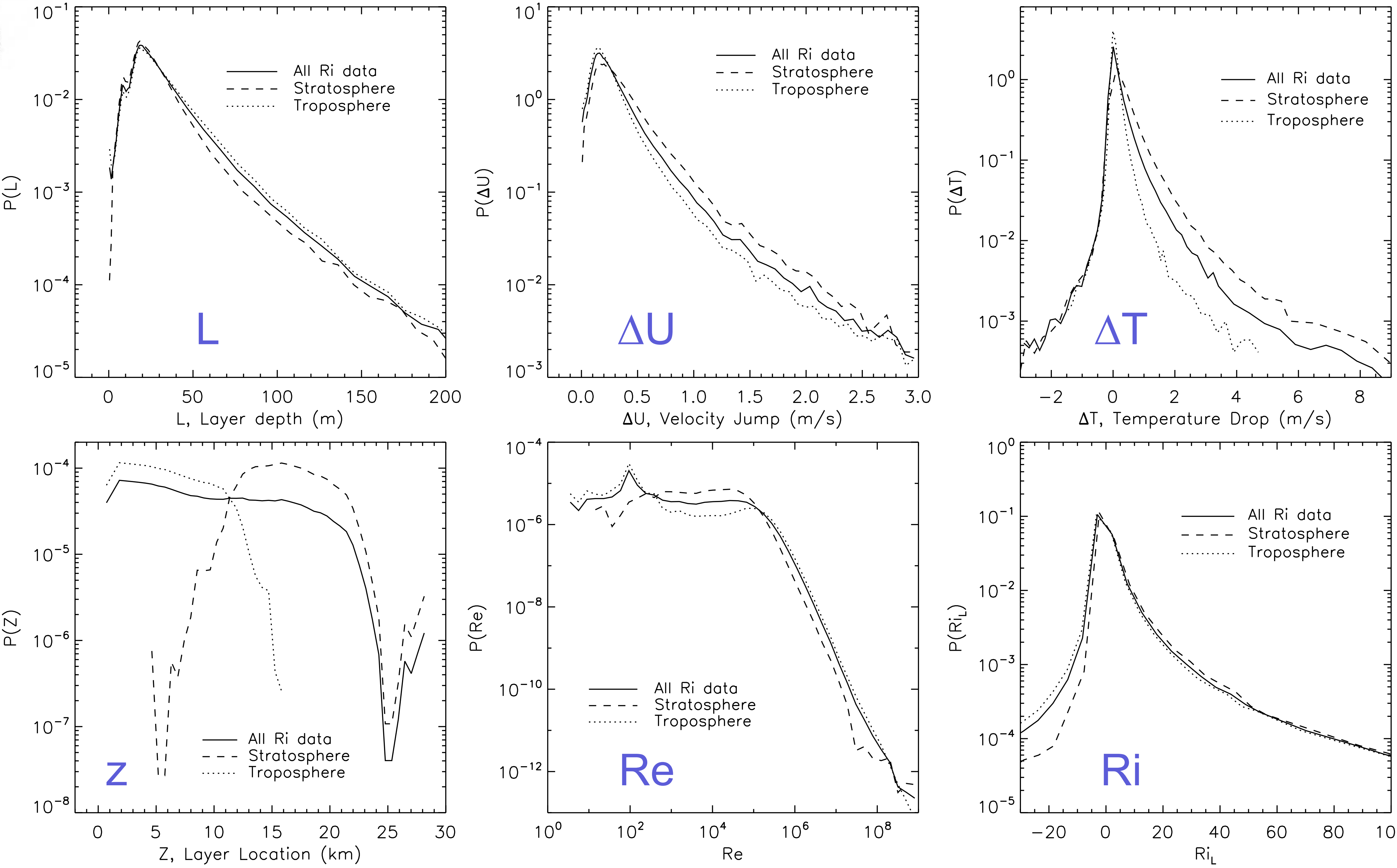


C_T^2 T R_i



CAT layers: What are their characteristics?

Data from 350 balloon profiles from VTMX, Salt Lake City, Utah, Oct 2000. Identical results obtained with CASES-99 data, Kansas, Oct 1999, despite much flatter terrain.

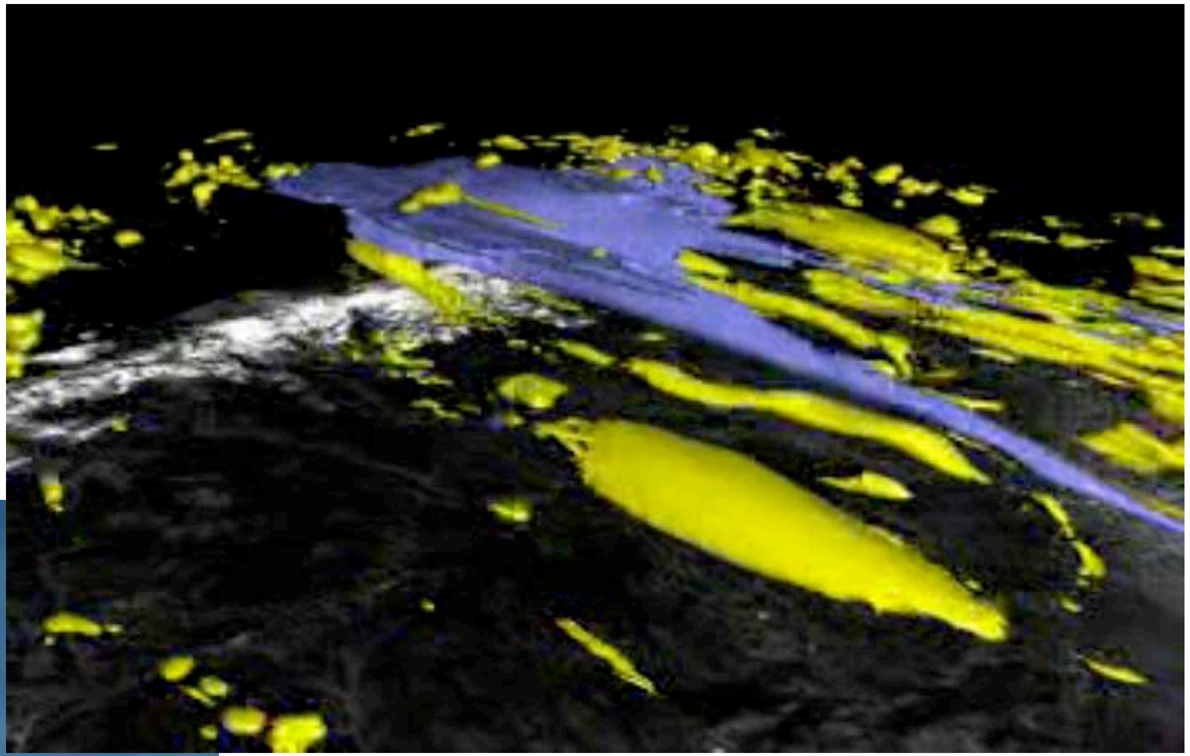


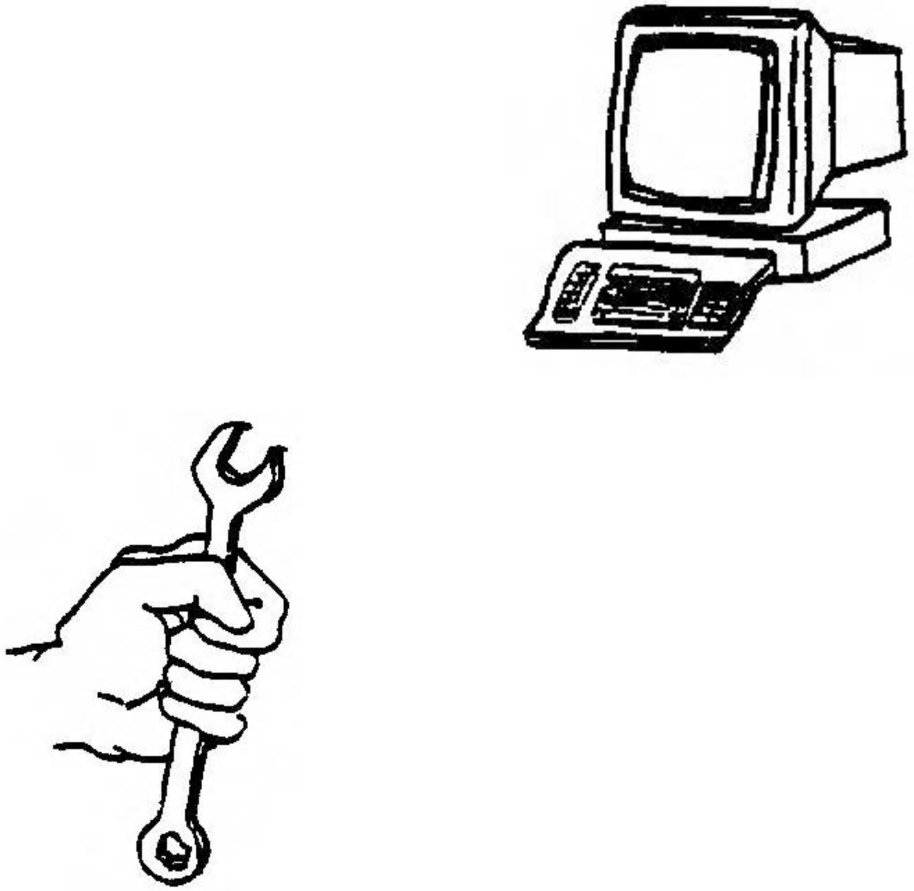
Unresolved CAT: Is It Important?

1992 CAT Event

- 9 Dec 1992 Front Range windstorm, Evergreen, CO
- DC-8 Cargo aircraft encounters two full minutes of intense turbulence
- Left engine and 12-feet of wing ripped from plane
- Pilot landed safely at Stapleton

Clark, et al., J. Atmos. Sci. 57 1105-1131 (2000)





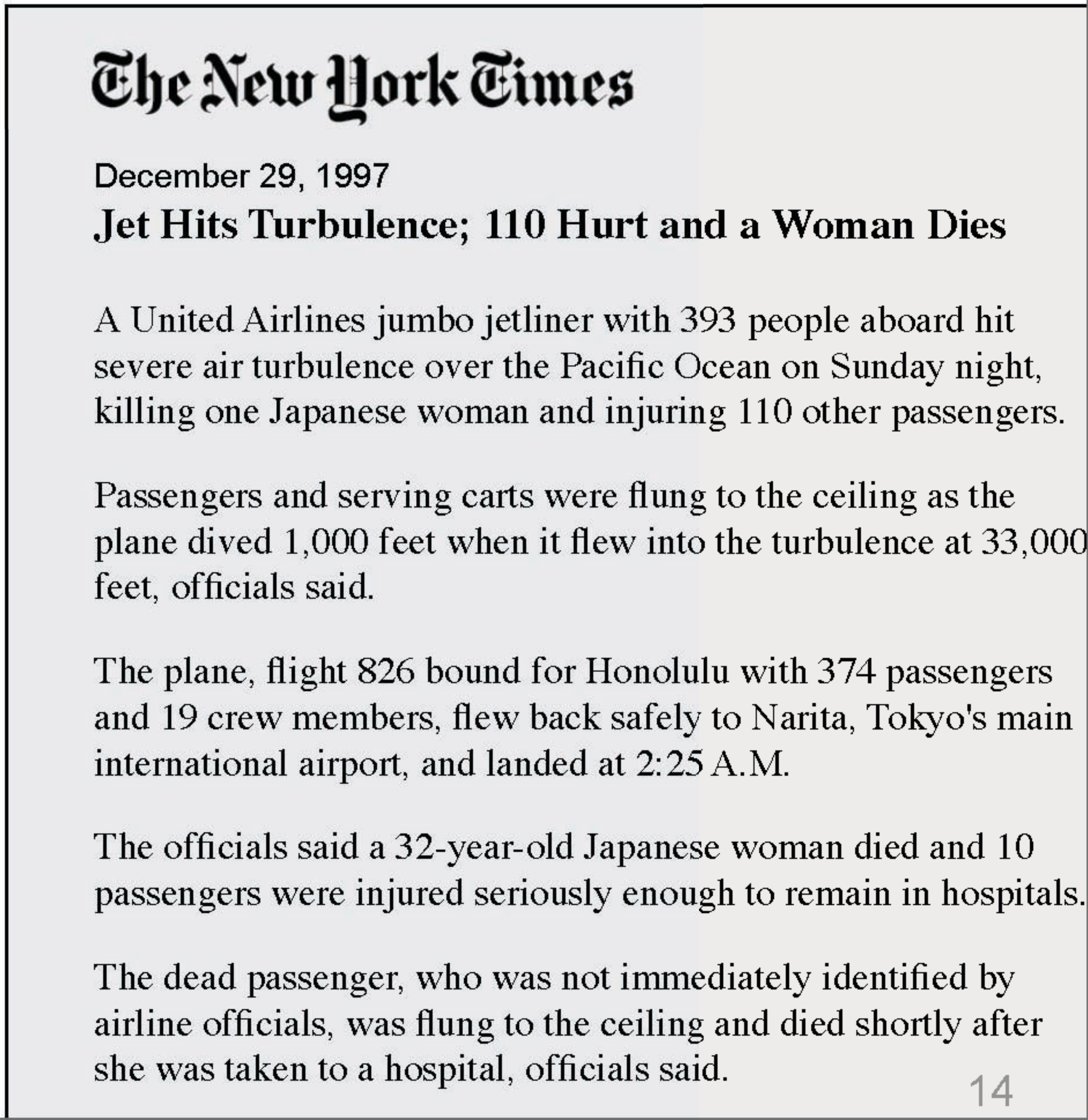
Unresolved CAT: Is It Important?

50 years of U2 flights

- U2 reconnaissance - 50 years of high-altitude experience
- Many aborted missions due to high-altitude wave activity
- Damaged / destroyed aircraft
- One pilot killed

1997 CAT Event

- 29 Dec 1997, United flight 826 to Honolulu from Japan
- Boeing 747 encountered severe turbulence at 33,000 ft
- Dropped 1000 ft, 110 passengers injured, 1 killed



The New York Times

December 29, 1997

Jet Hits Turbulence; 110 Hurt and a Woman Dies

A United Airlines jumbo jetliner with 393 people aboard hit severe air turbulence over the Pacific Ocean on Sunday night, killing one Japanese woman and injuring 110 other passengers.

Passengers and serving carts were flung to the ceiling as the plane dived 1,000 feet when it flew into the turbulence at 33,000 feet, officials said.

The plane, flight 826 bound for Honolulu with 374 passengers and 19 crew members, flew back safely to Narita, Tokyo's main international airport, and landed at 2:25 A.M.

The officials said a 32-year-old Japanese woman died and 10 passengers were injured seriously enough to remain in hospitals.

The dead passenger, who was not immediately identified by airline officials, was flung to the ceiling and died shortly after she was taken to a hospital, officials said.

Unresolved CAT: Is It Important?

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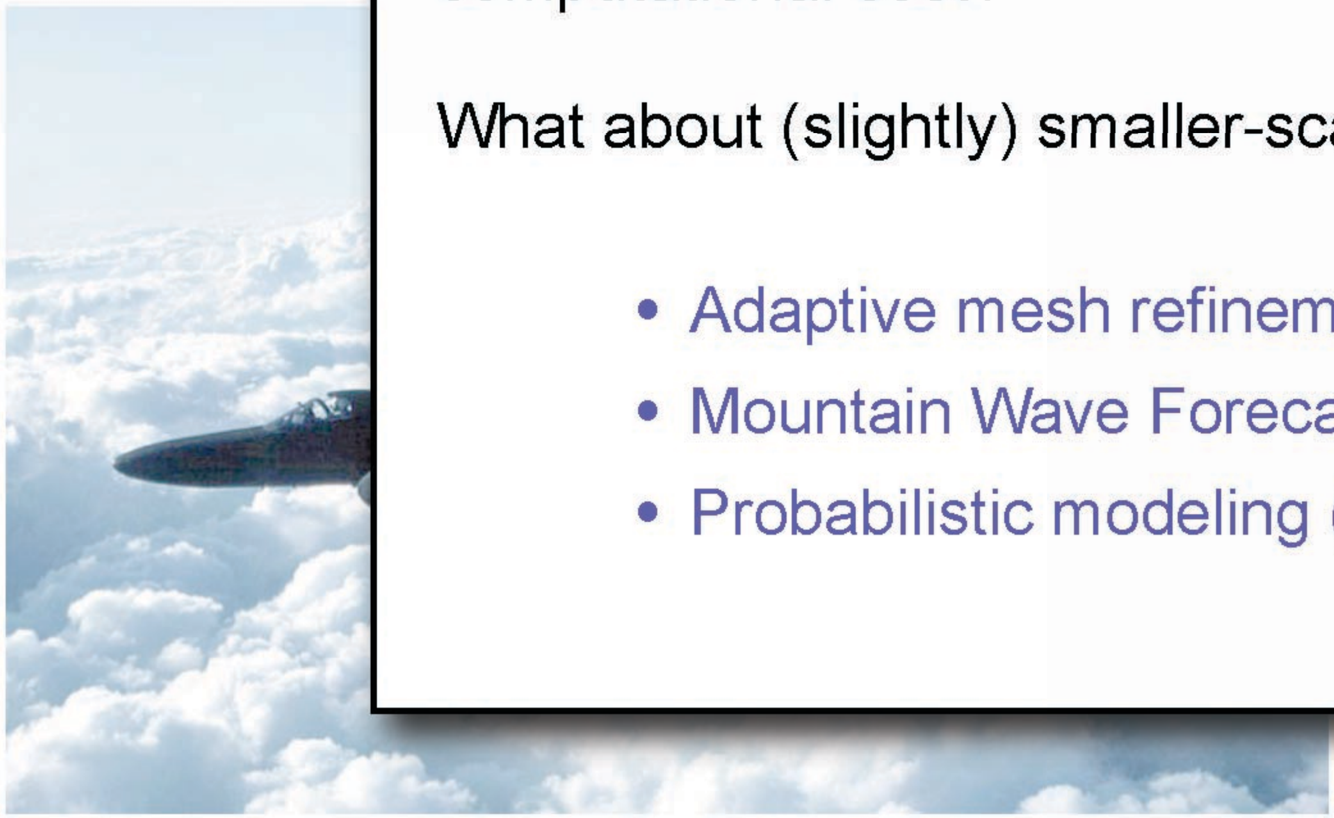

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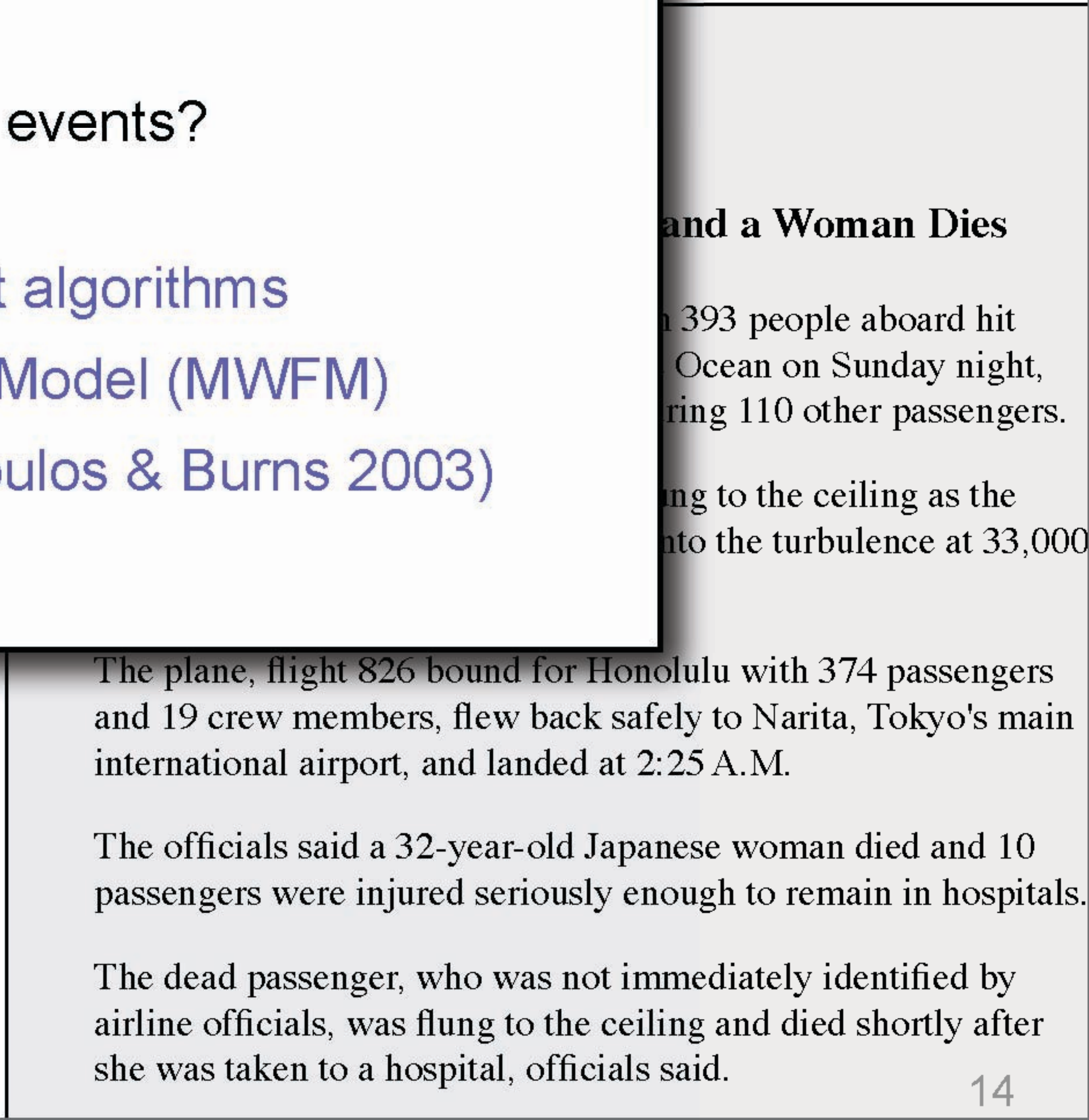

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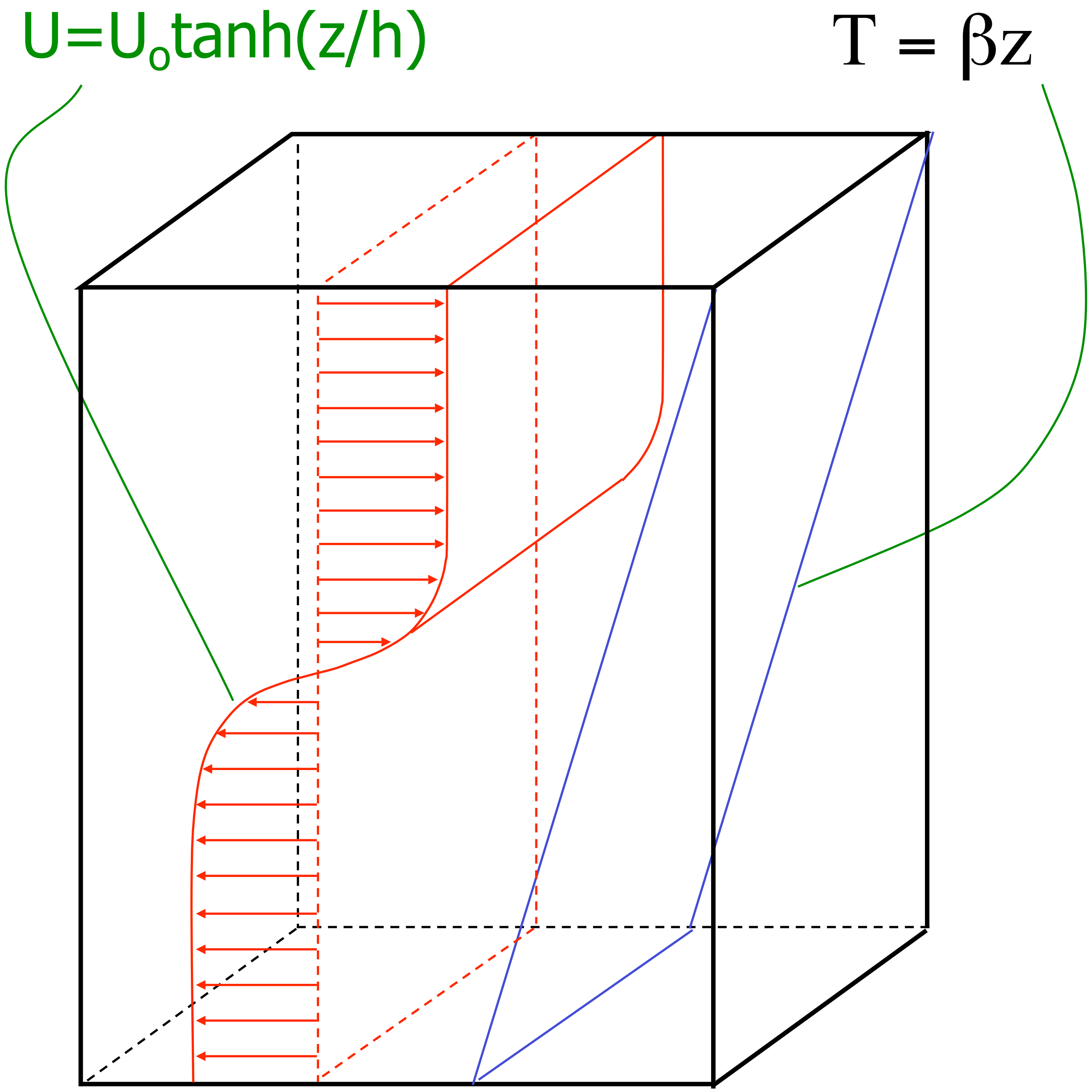
What can we do about simulating/modeling?

Can we anticipate intense events without increasing computational cost?

What about (slightly) smaller-scale events?

- Adaptive mesh refinement algorithms
- Mountain Wave Forecast Model (MWFM)
- Probabilistic modeling (Poulos & Burns 2003)

Wind Shear Simulation



- Stream-function/vorticity formulation of the Boussinesq equations
- Fully spectral, 3D FFT’s = 80% cost
- Radix 2,3,4,5 FFTs
- Spectral modes and NCPUs must be commensurate
- Communication: shmem and MPI, global transpose (all-to-all), data reduction
- Parallel I/O every ~ 60 δt
- Up to 4000 x 2000 x 2000 modes
- 6 Grand Challenge and 2 DoD CAP awards
- Logged over 10 million CPU hours; generated over 300 Tbytes of archived data

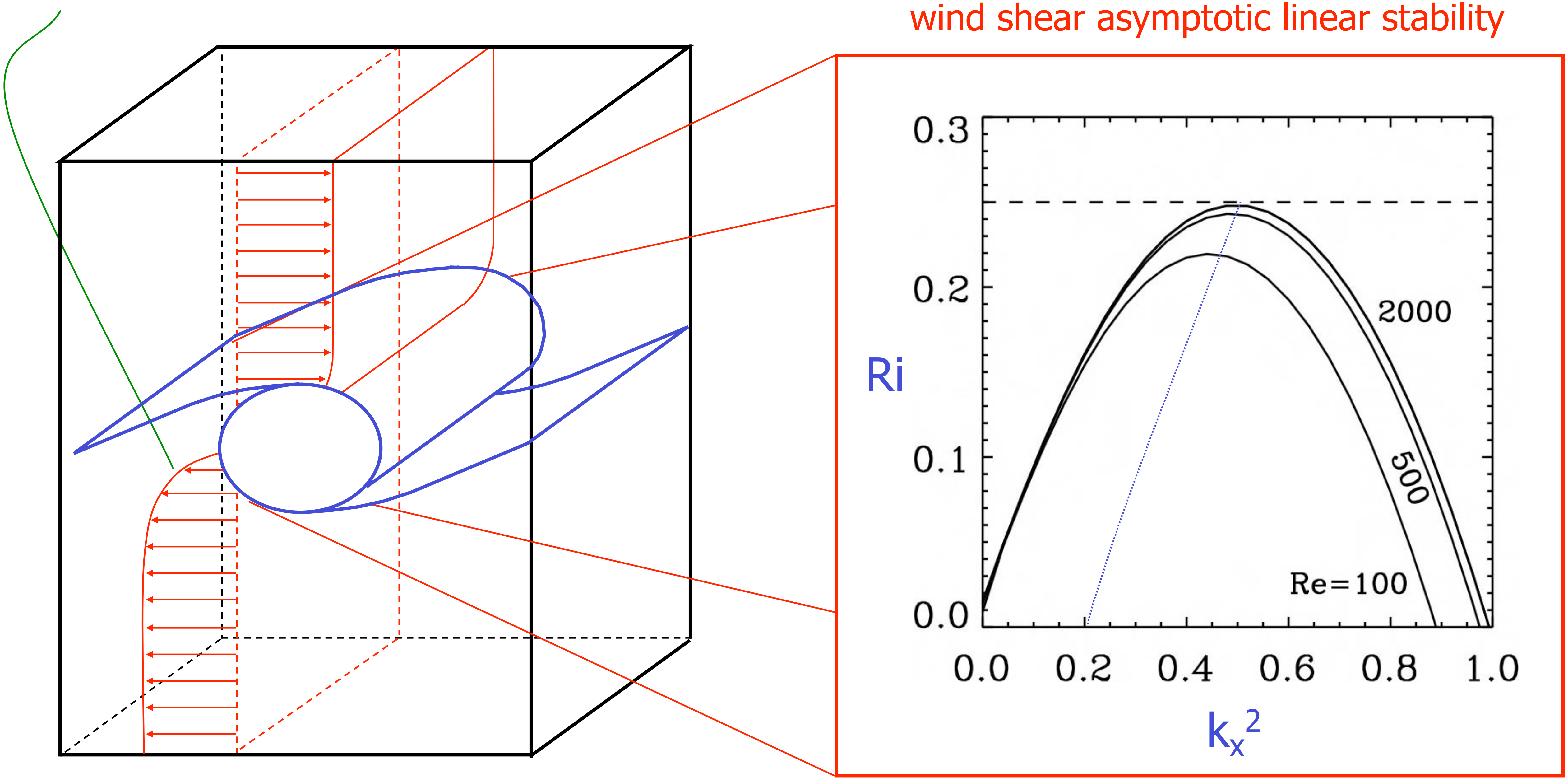
$$Ri = \frac{N^2h^2}{U_0^2} \qquad Re = \frac{U_0 h}{\nu} \qquad Pe = \frac{U_0 h}{\kappa}$$

$$\begin{aligned} \partial_t u + \omega \times u &= Re^{-1}\nabla^2 u - \nabla P + Ri\,\theta\,\hat{z} \\ \partial_t \theta + u \cdot \nabla\theta &= Pe^{-1}\nabla^2\theta \\ \nabla \cdot u &= 0 \end{aligned}$$

Wind Shear Simulation

$U = U_o \tanh(z/h)$

wind shear asymptotic linear stability



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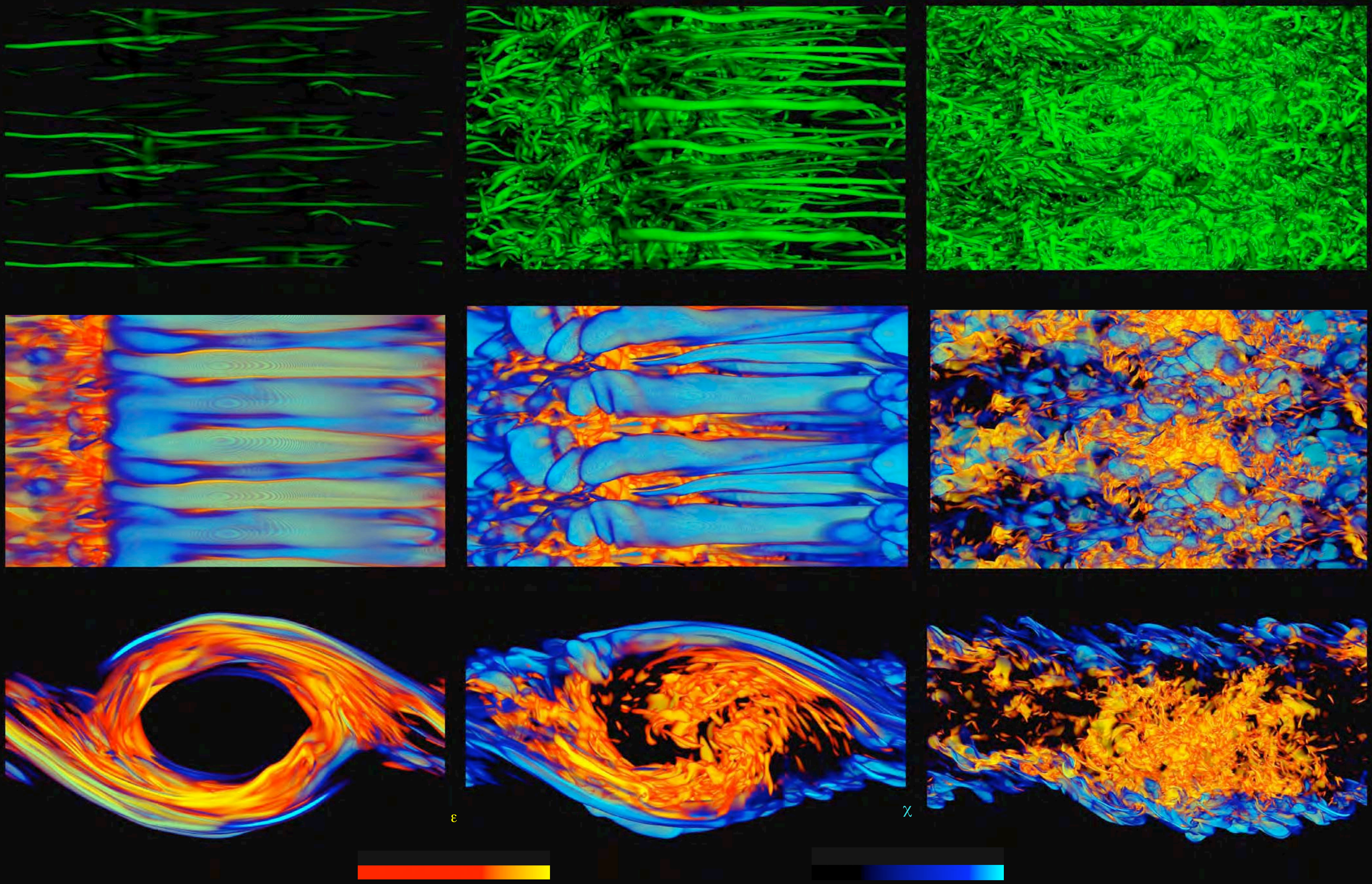
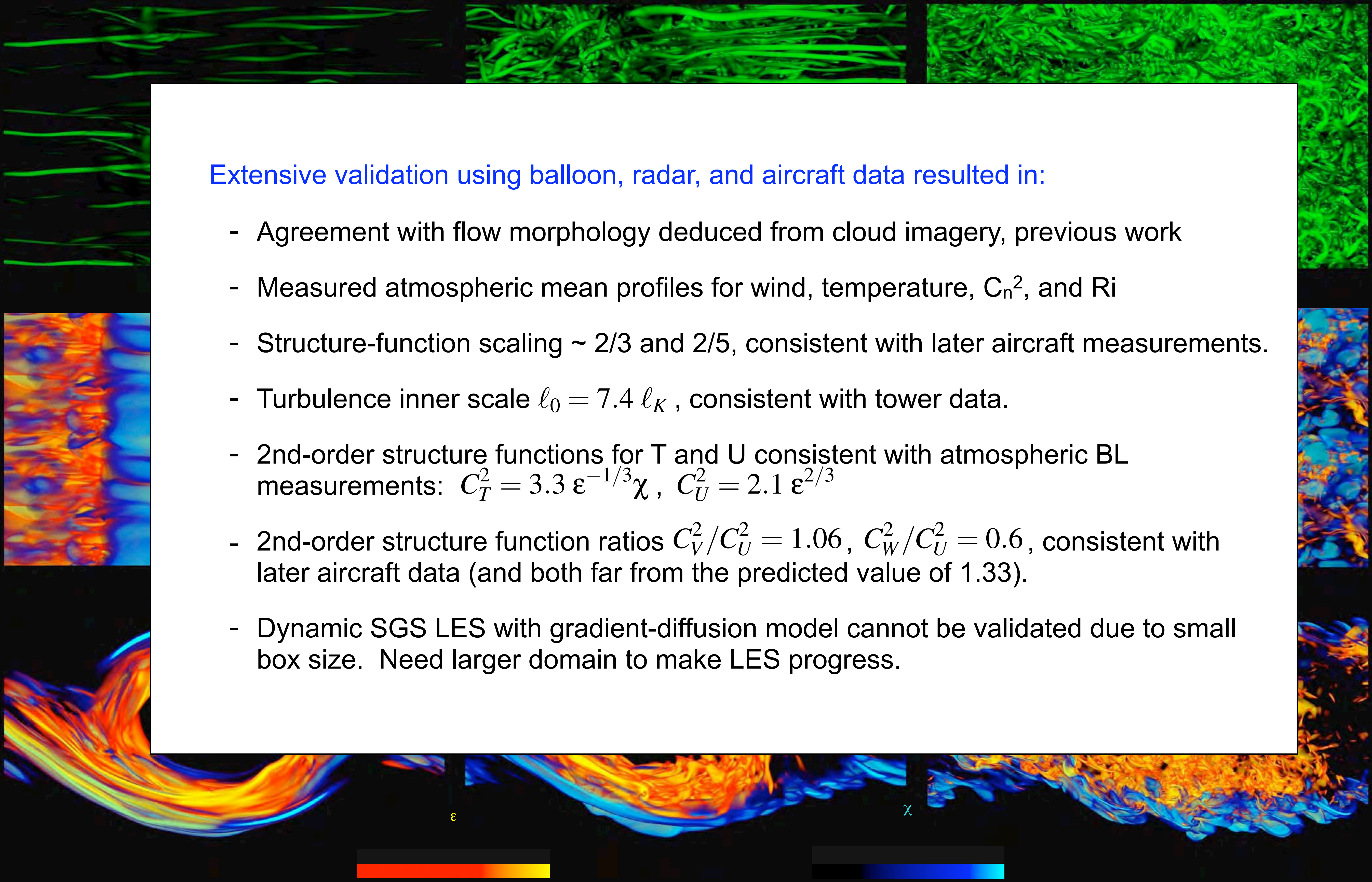
Hi-Res Wind-Shear Simulations



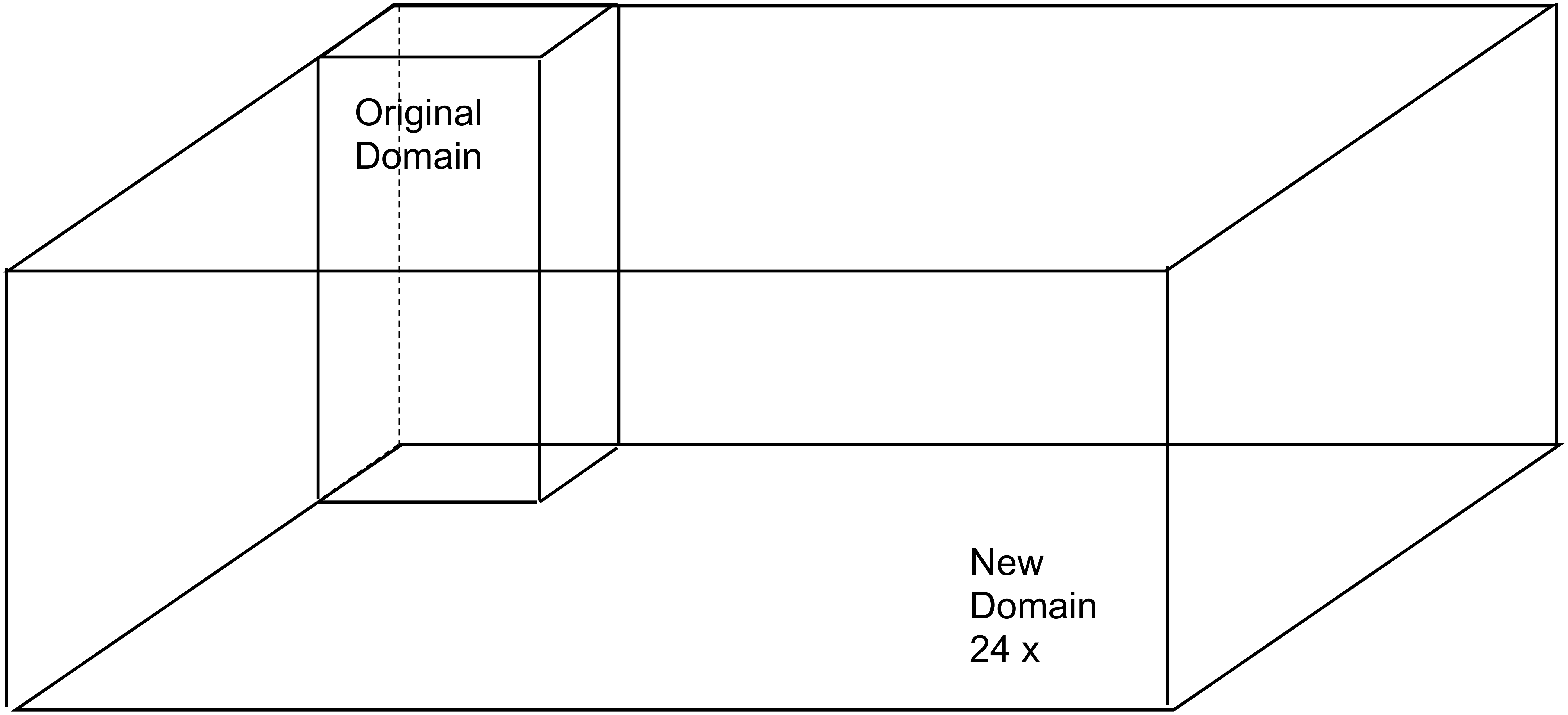
Hi-Res Wind-Shear Simulations



Extensive validation using balloon, radar, and aircraft data resulted in:

- Agreement with flow morphology deduced from cloud imagery, previous work
- Measured atmospheric mean profiles for wind, temperature, C_n^2, and Ri
- Structure-function scaling ~ 2/3 and 2/5, consistent with later aircraft measurements.
- Turbulence inner scale $\ell_0 = 7.4\,\ell_K$, consistent with tower data.
- 2nd-order structure functions for T and U consistent with atmospheric BL measurements: $C_T^2 = 3.3\,\varepsilon^{-1/3}\chi$, $C_U^2 = 2.1\,\varepsilon^{2/3}$
- 2nd-order structure function ratios $C_V^2/C_U^2 = 1.06$, $C_W^2/C_U^2 = 0.6$, consistent with later aircraft data (and both far from the predicted value of 1.33).
- Dynamic SGS LES with gradient-diffusion model cannot be validated due to small box size. Need larger domain to make LES progress.

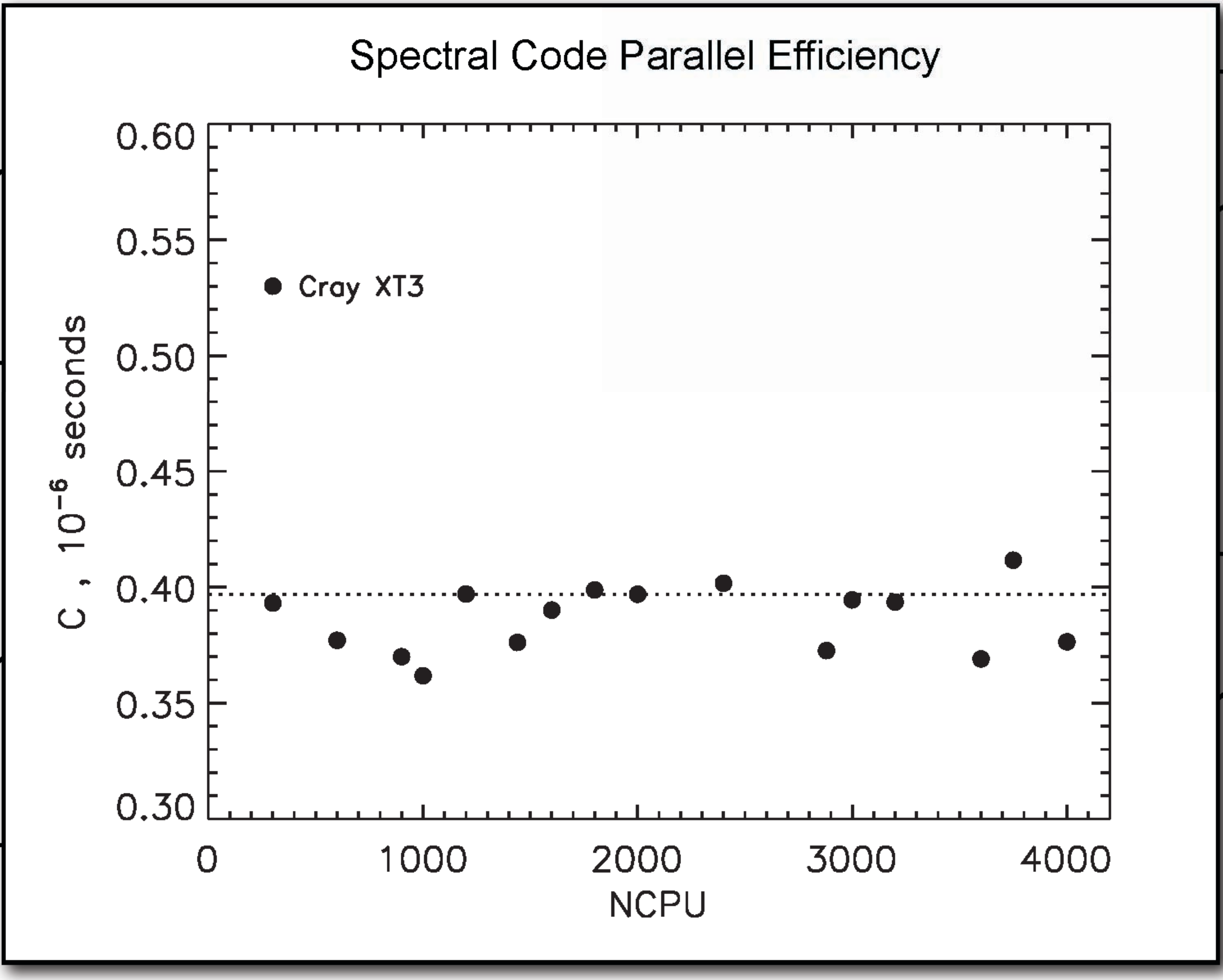
DoD CAP Wind-Shear Simulations

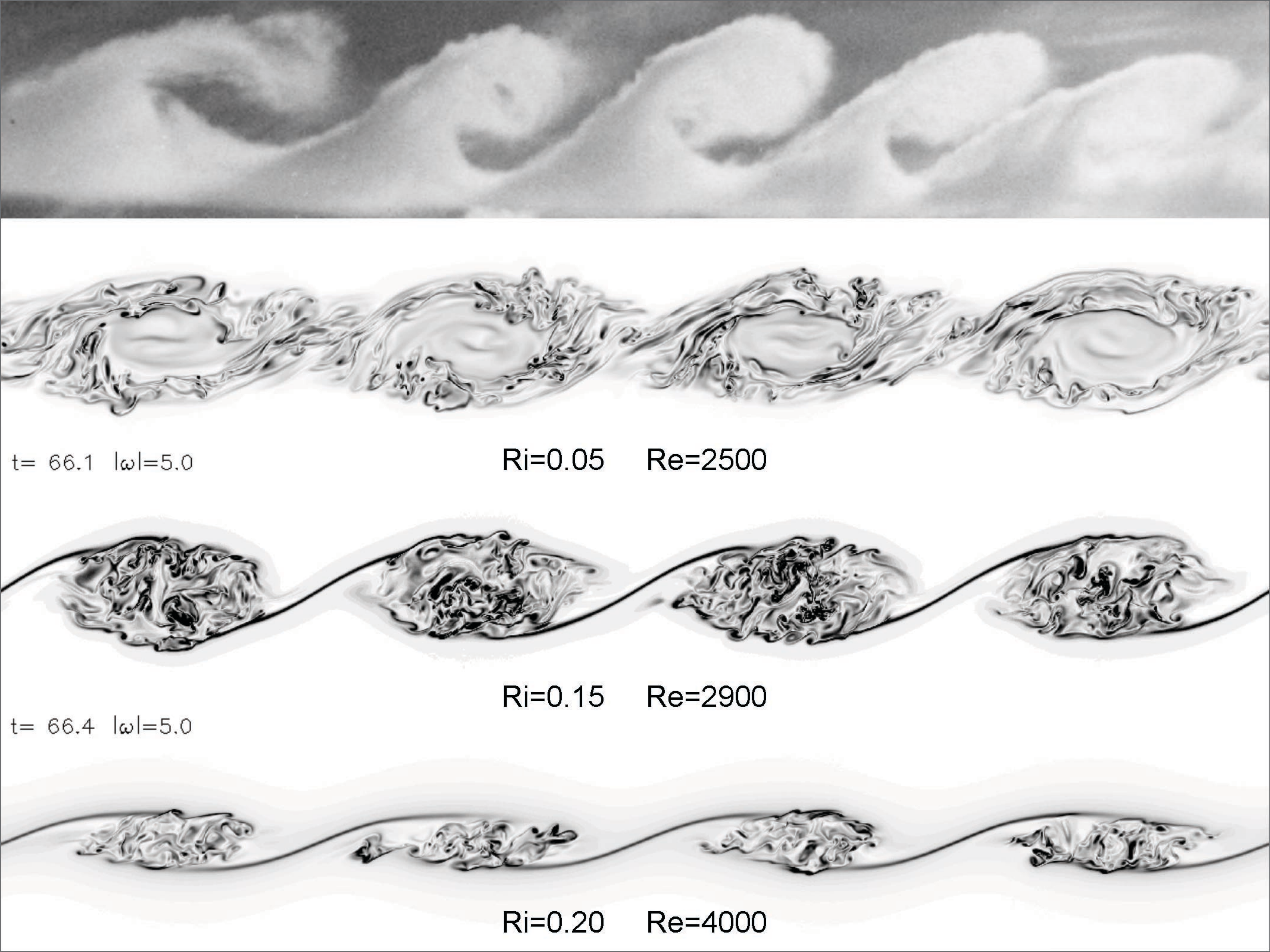


Original Domain

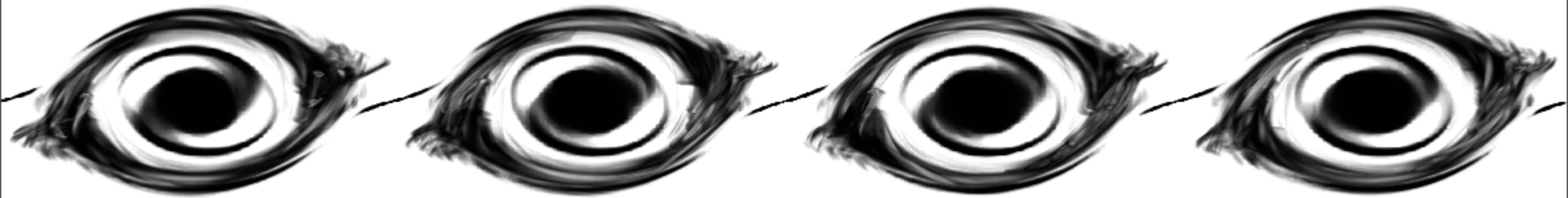
New Domain 24 x

DoD CAP Wind-Shear Simulations

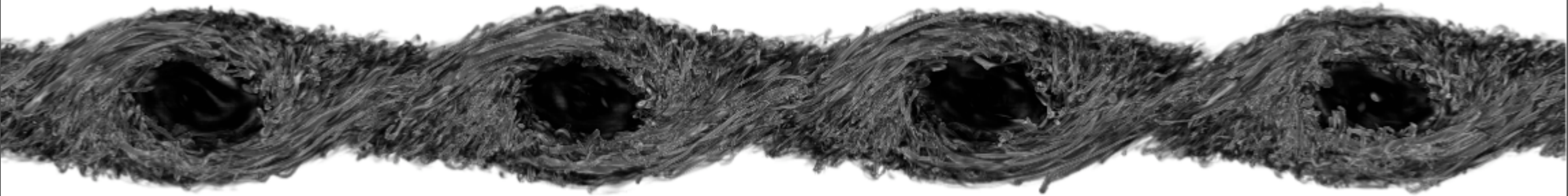



t= 66.1 |ω|=5.0
Ri=0.05 Re=2500
Ri=0.15 Re=2900
t= 66.4 |ω|=5.0
Ri=0.20 Re=4000

Vortex tubes viewed from above, Ri=0.05



t=54 : secondary instability



t=68 : KE, PE local minima

t=85 : KE, PE secondary maxima

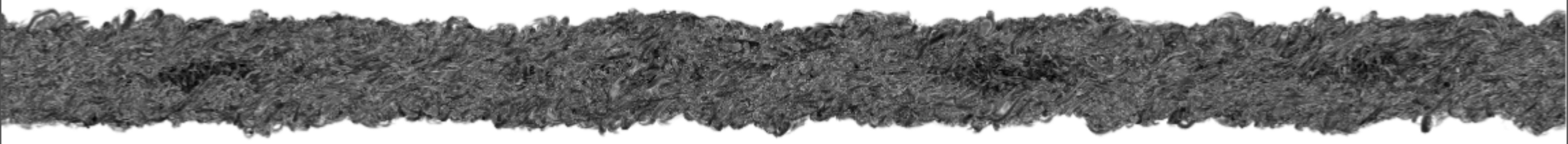
t=111 : turbulence intensity and vorticity maxima

Vortex tubes viewed from above, Ri=0.20

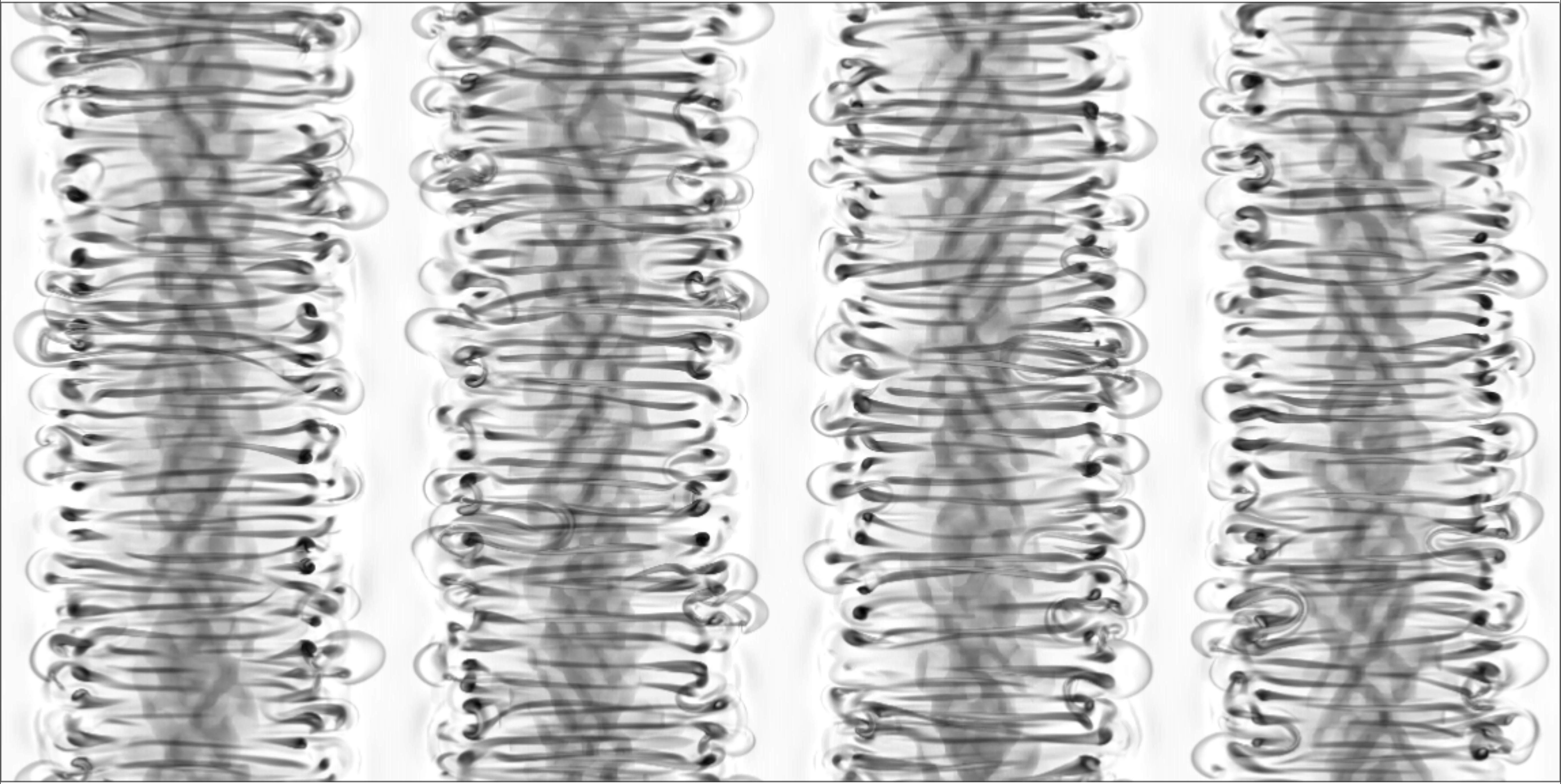

t=37 : maximum laminar amplitude


t=54 : maximum billow amplitude, turbulence erupts in billow cores


t=66 : PE peaks

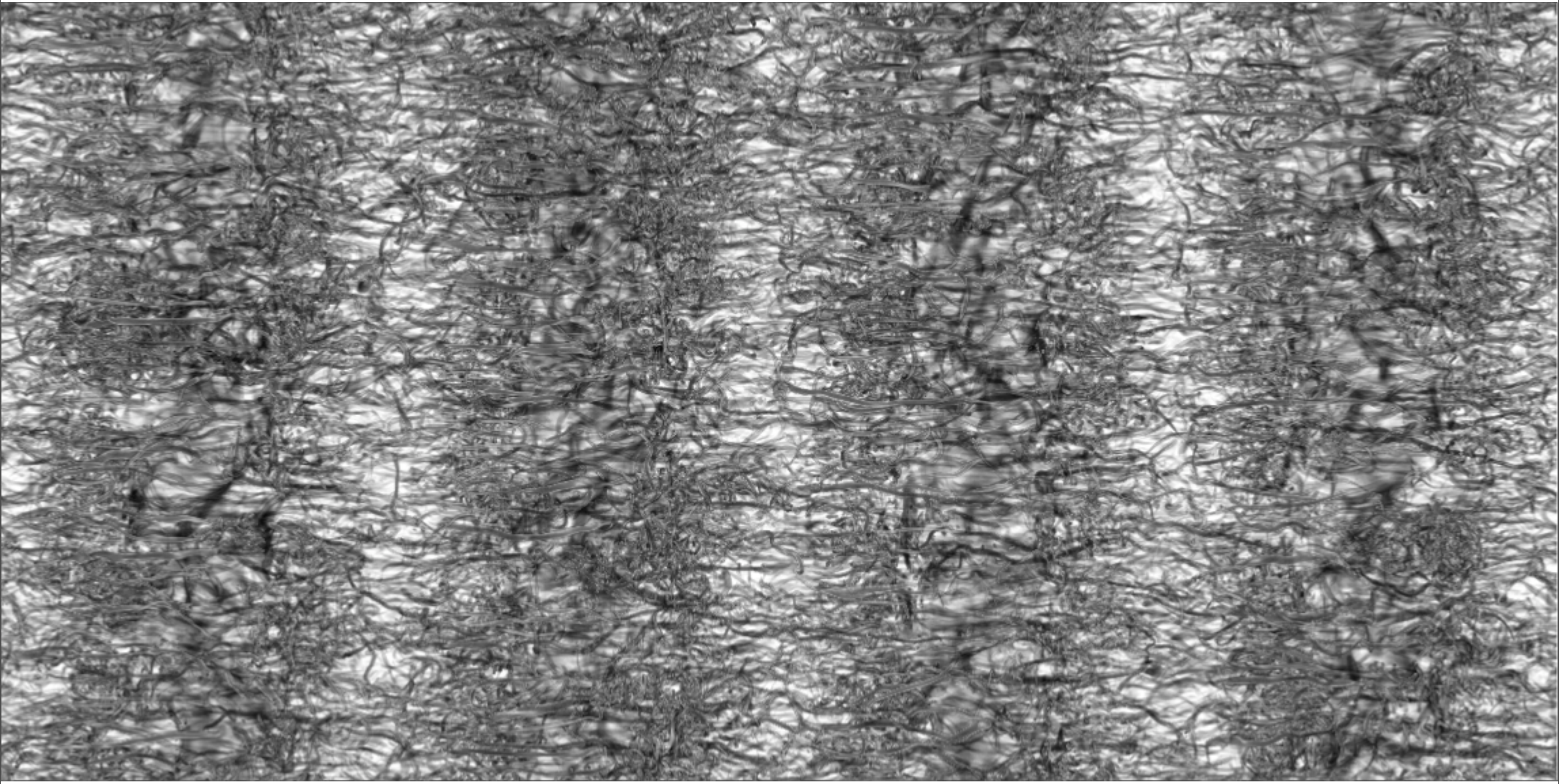

t=82 : turbulence reaches braids

Ri=0.05: vortex tubes viewed from above



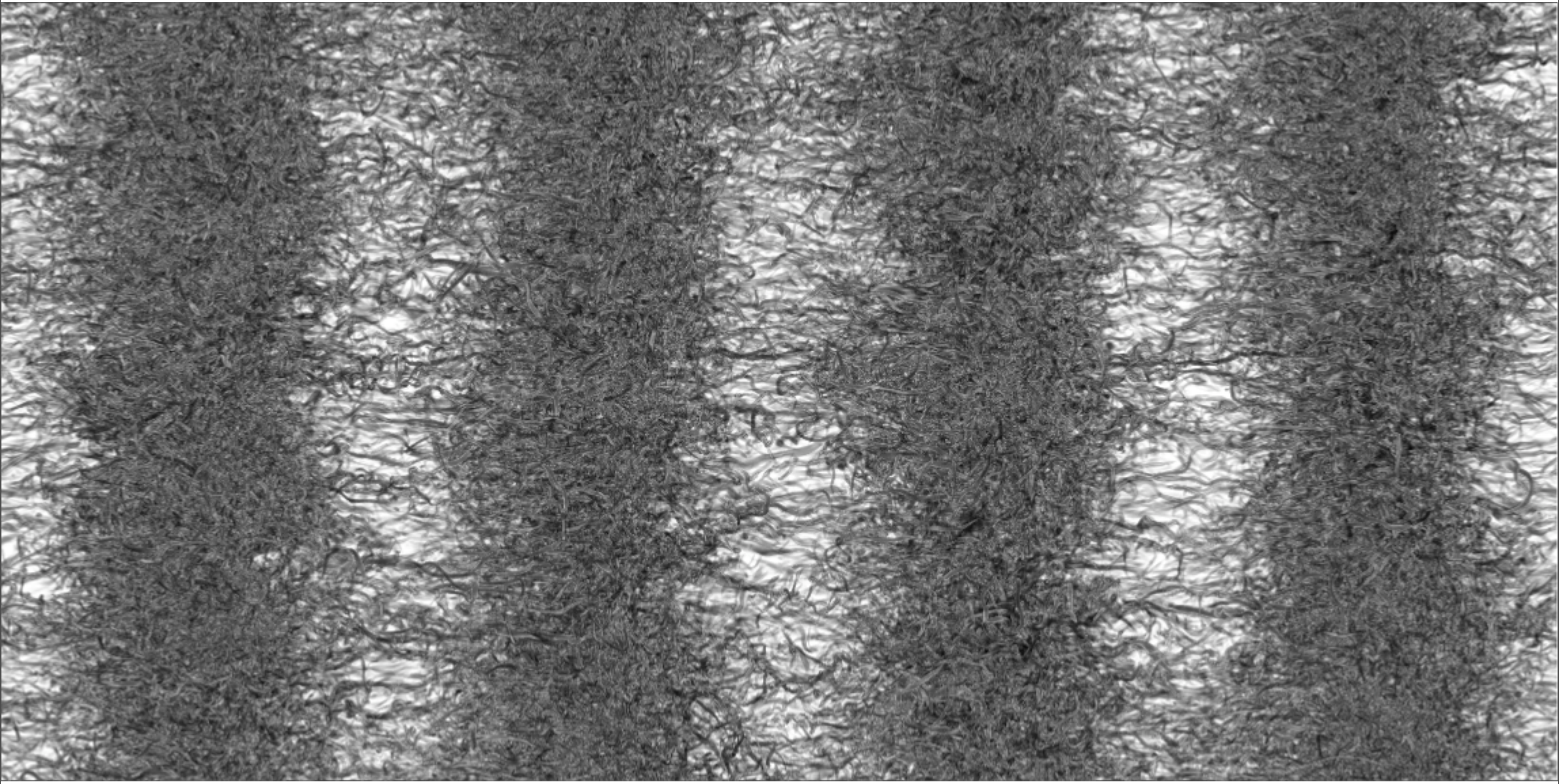
t=54 : secondary instability

Ri=0.05: vortex tubes viewed from above



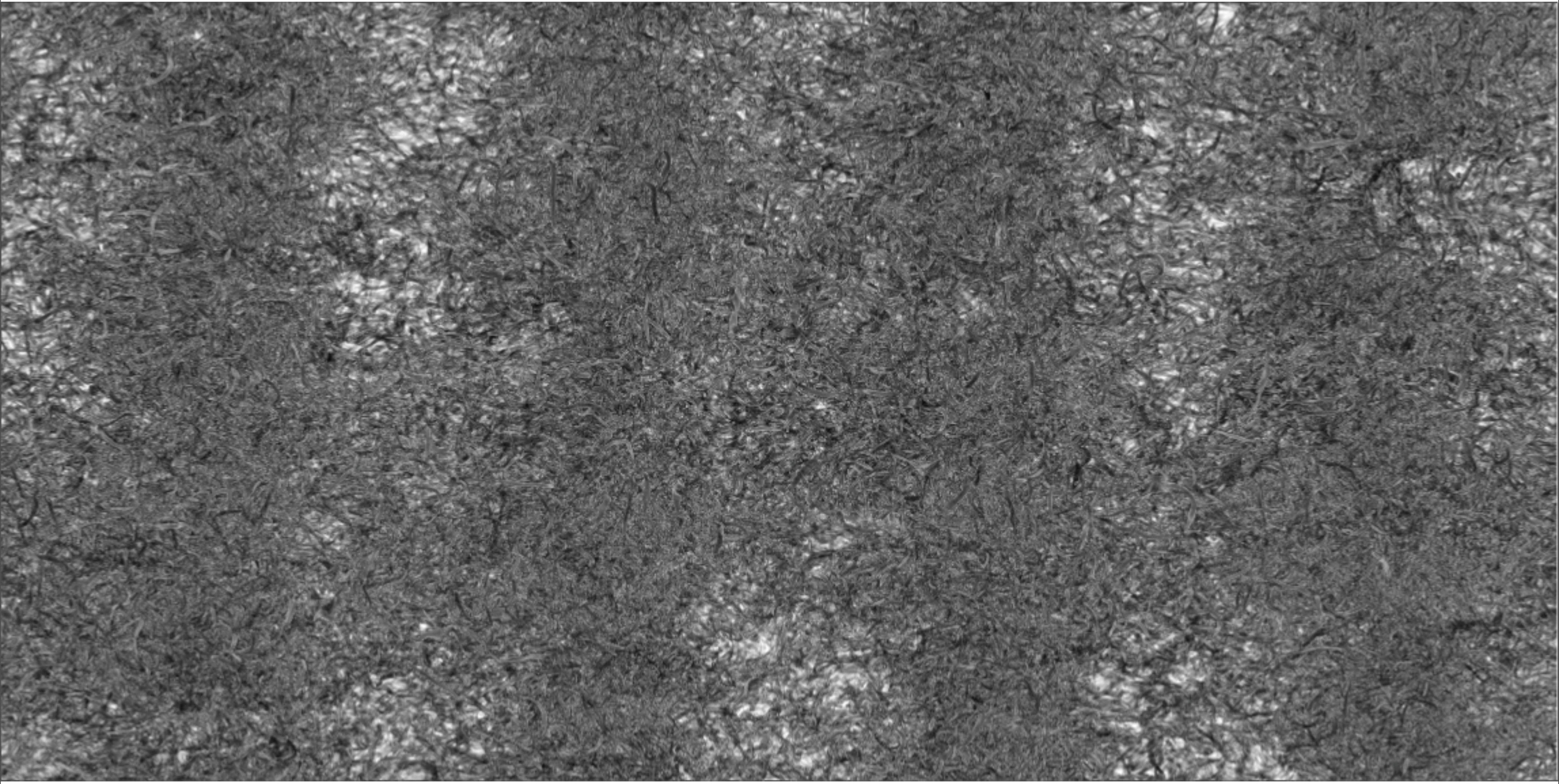
t=68 : KE, PE local minima

Ri=0.05: vortex tubes viewed from above



t=85 : KE, PE secondary maxima

Ri=0.05: vortex tubes viewed from above

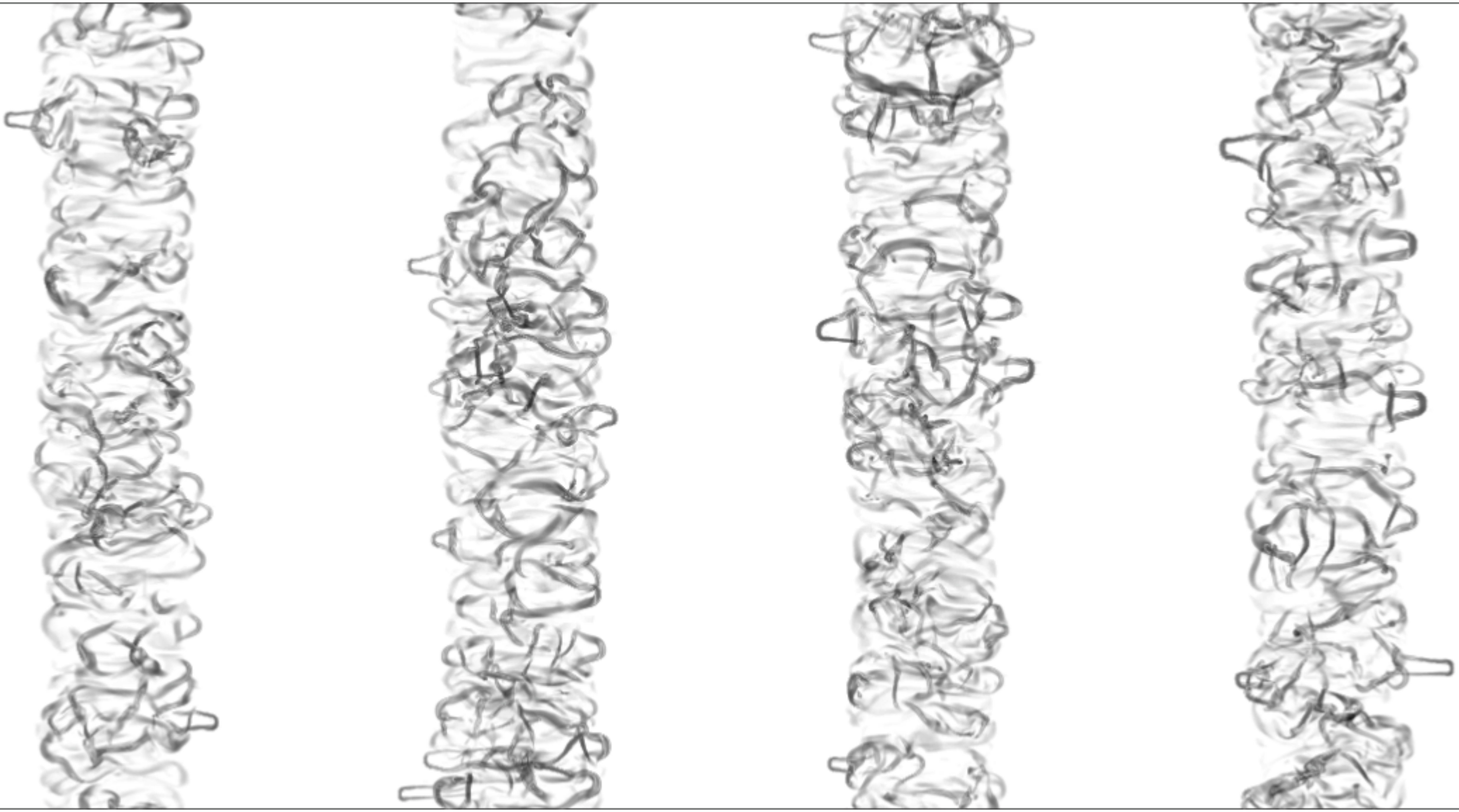


t=111 : turbulence intensity and vorticity maxima

Ri=0.20: vortex tubes viewed from above

t=37 : maximum laminar amplitude

Ri=0.20: vortex tubes viewed from above



t=54 : maximum billow amplitude, turbulence erupts in billow cores

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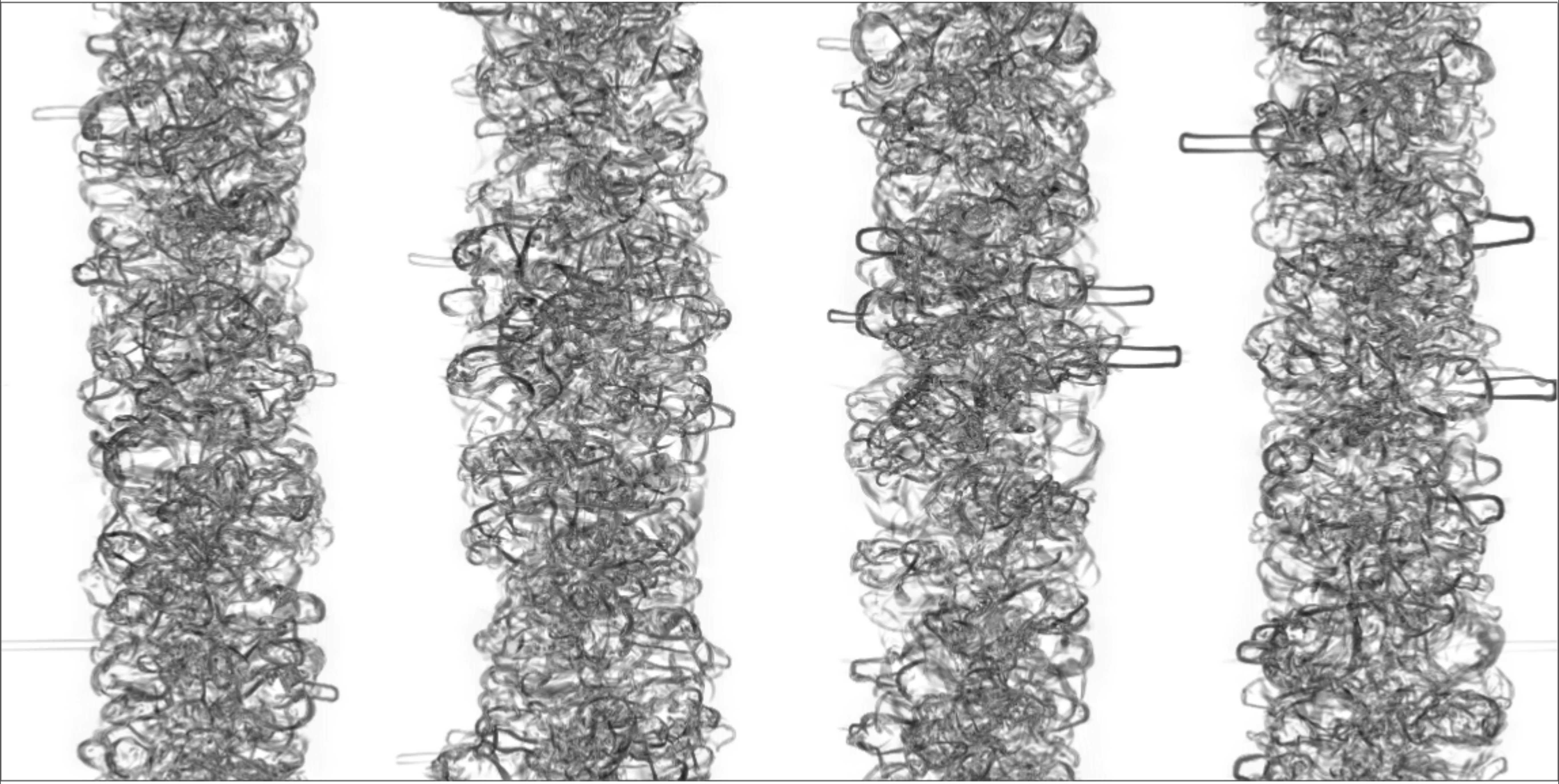
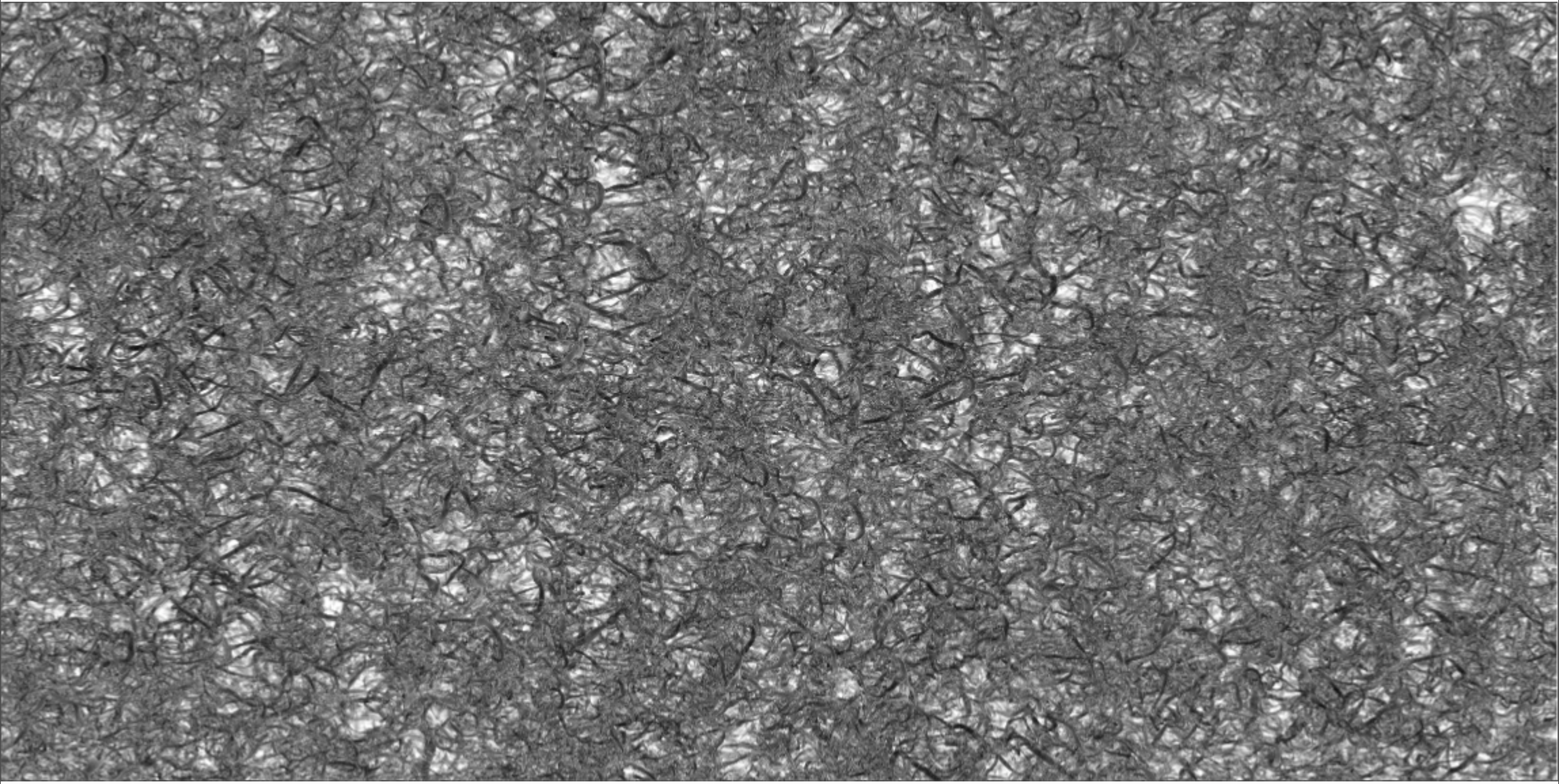


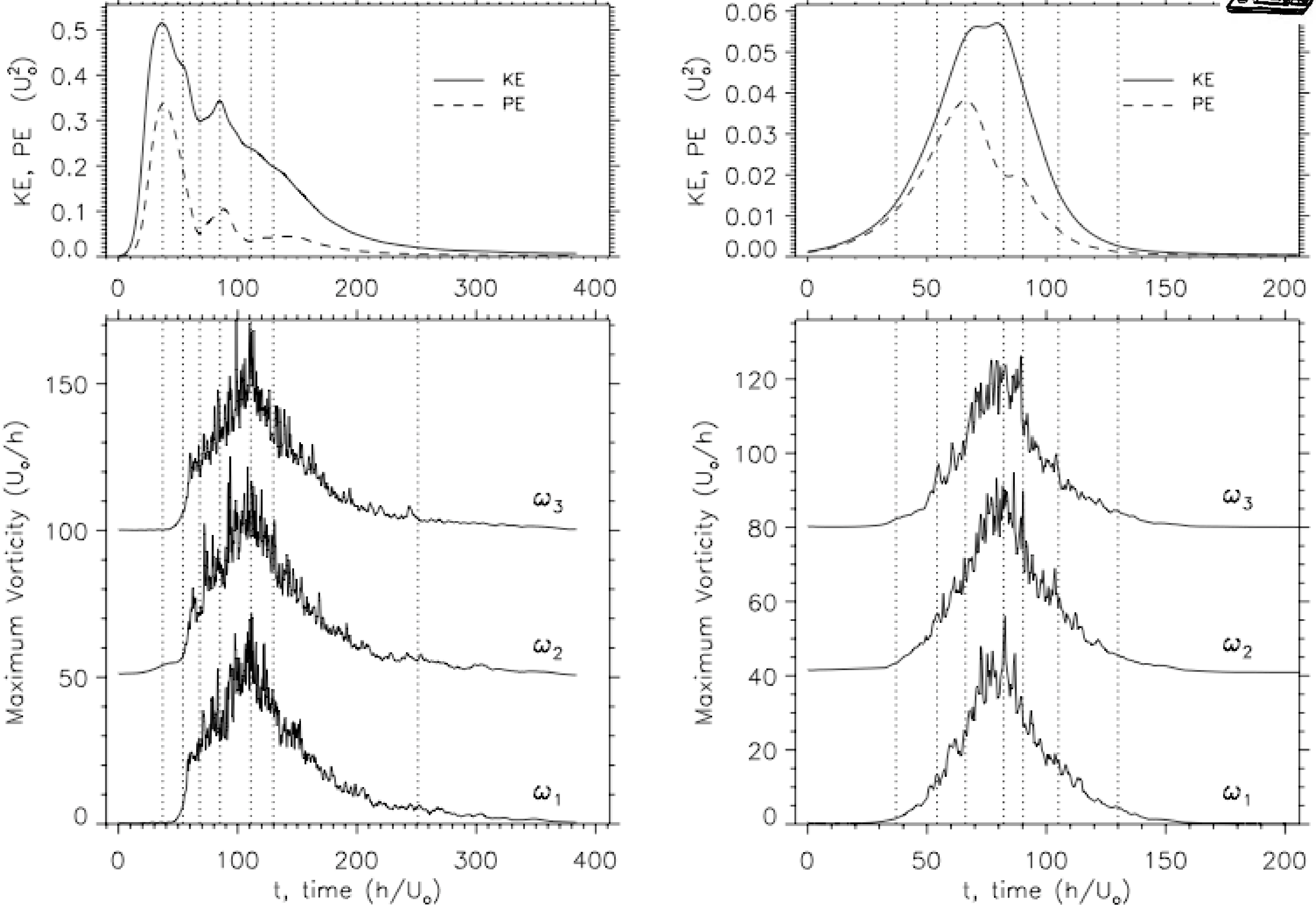
t=66 : PE peaks

Ri=0.20: vortex tubes viewed from above



t=82 : turbulence reaches braids

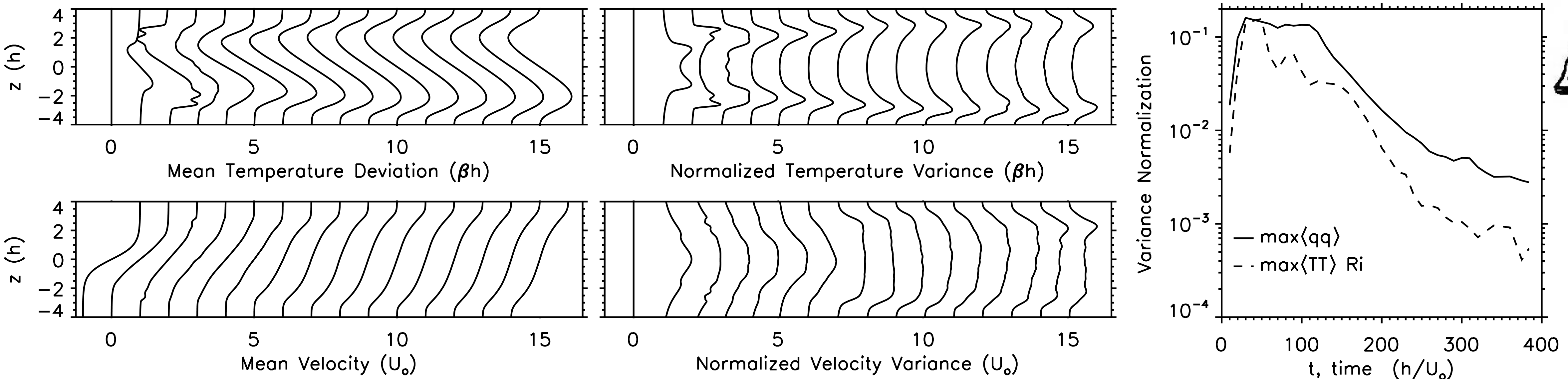
KE and max(ω) evolution

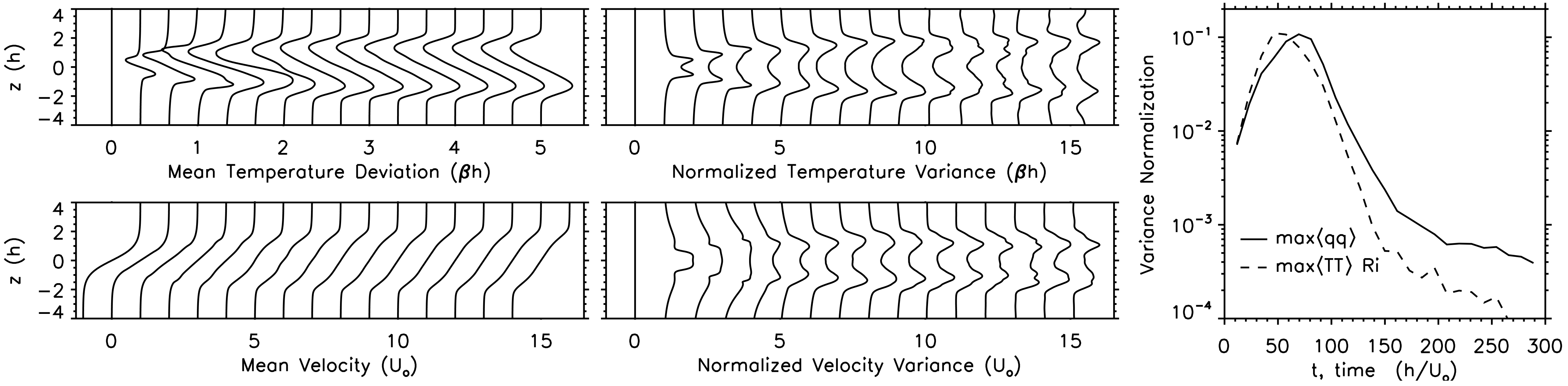


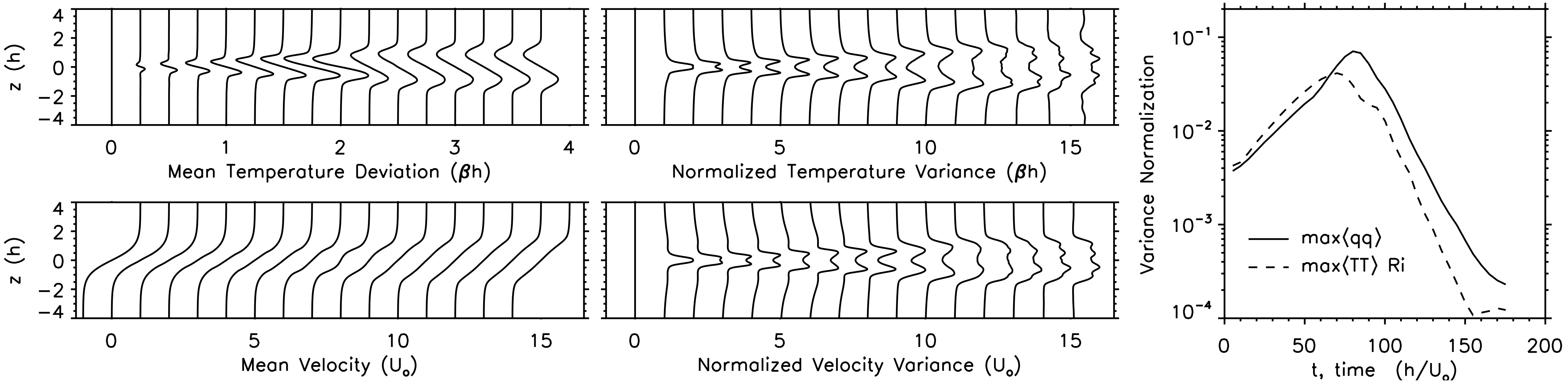
Ri=0.05

Ri=0.20

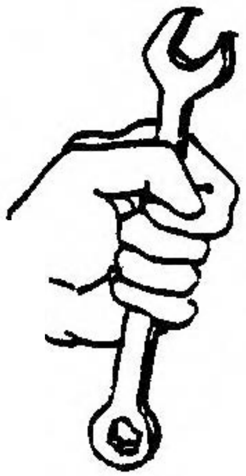
Mean and variance evolution



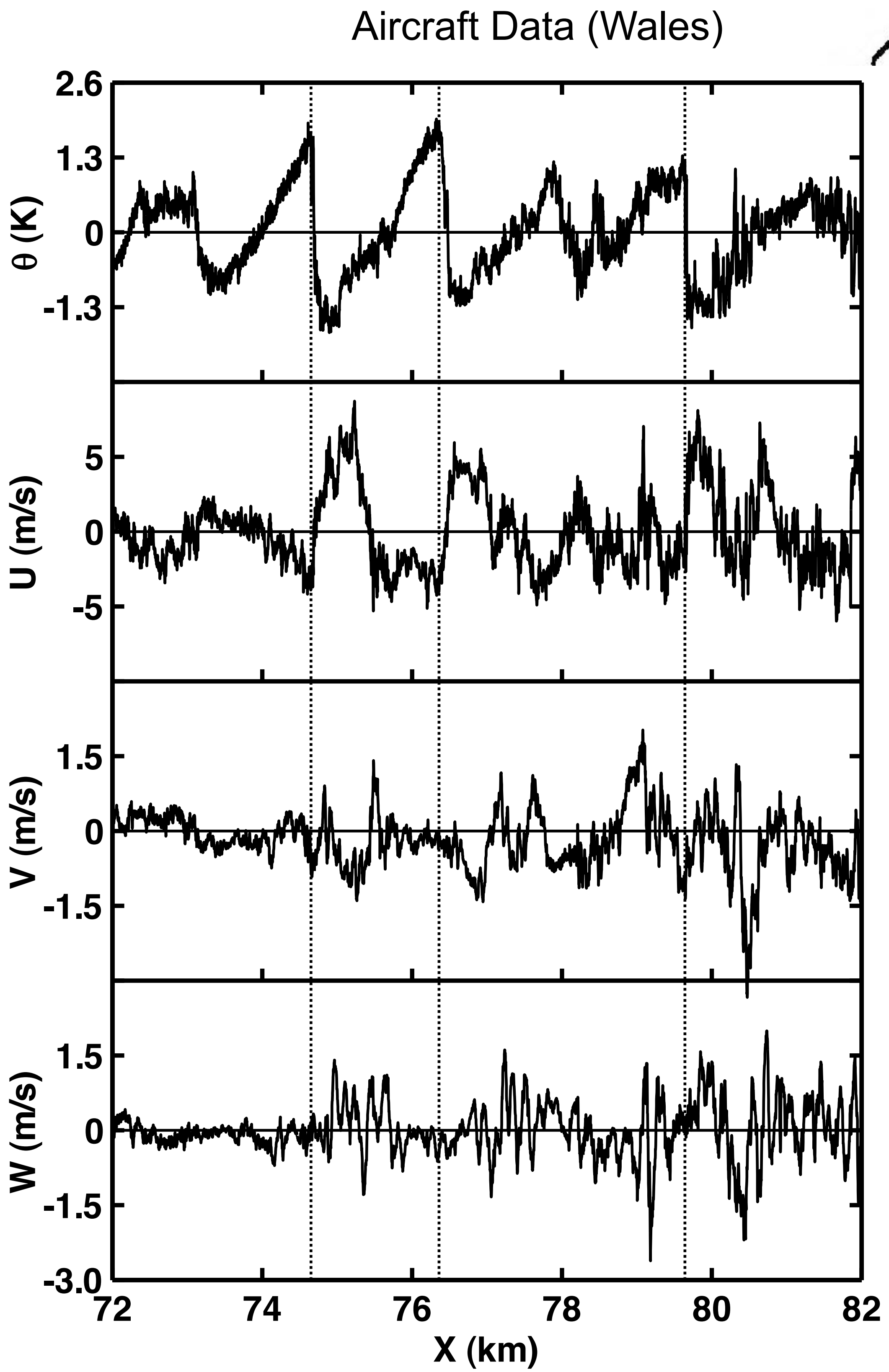




Comparison with Recent Aircraft Measurements

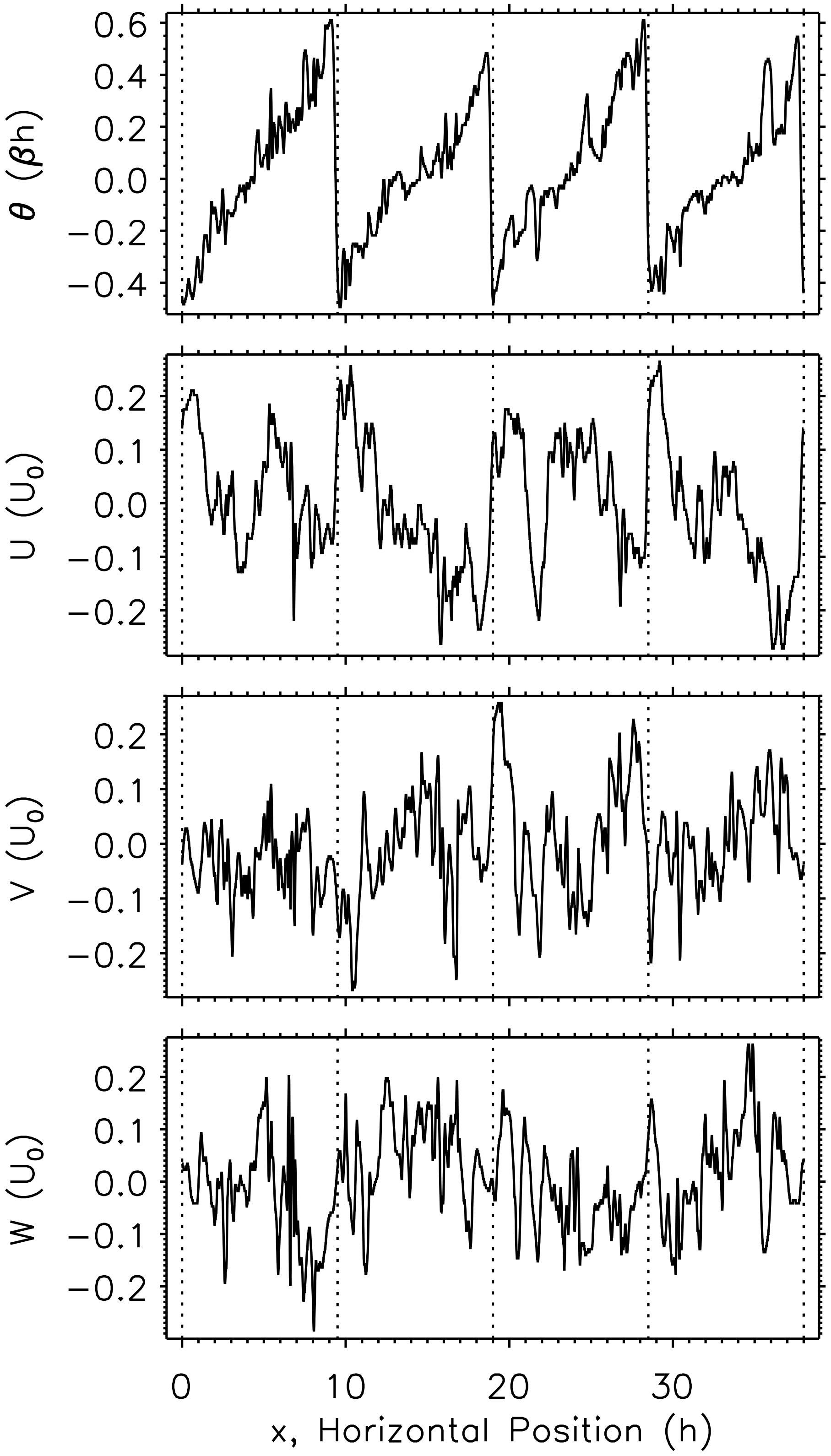


Grob G520T Egrett (Airborne Research Australia)

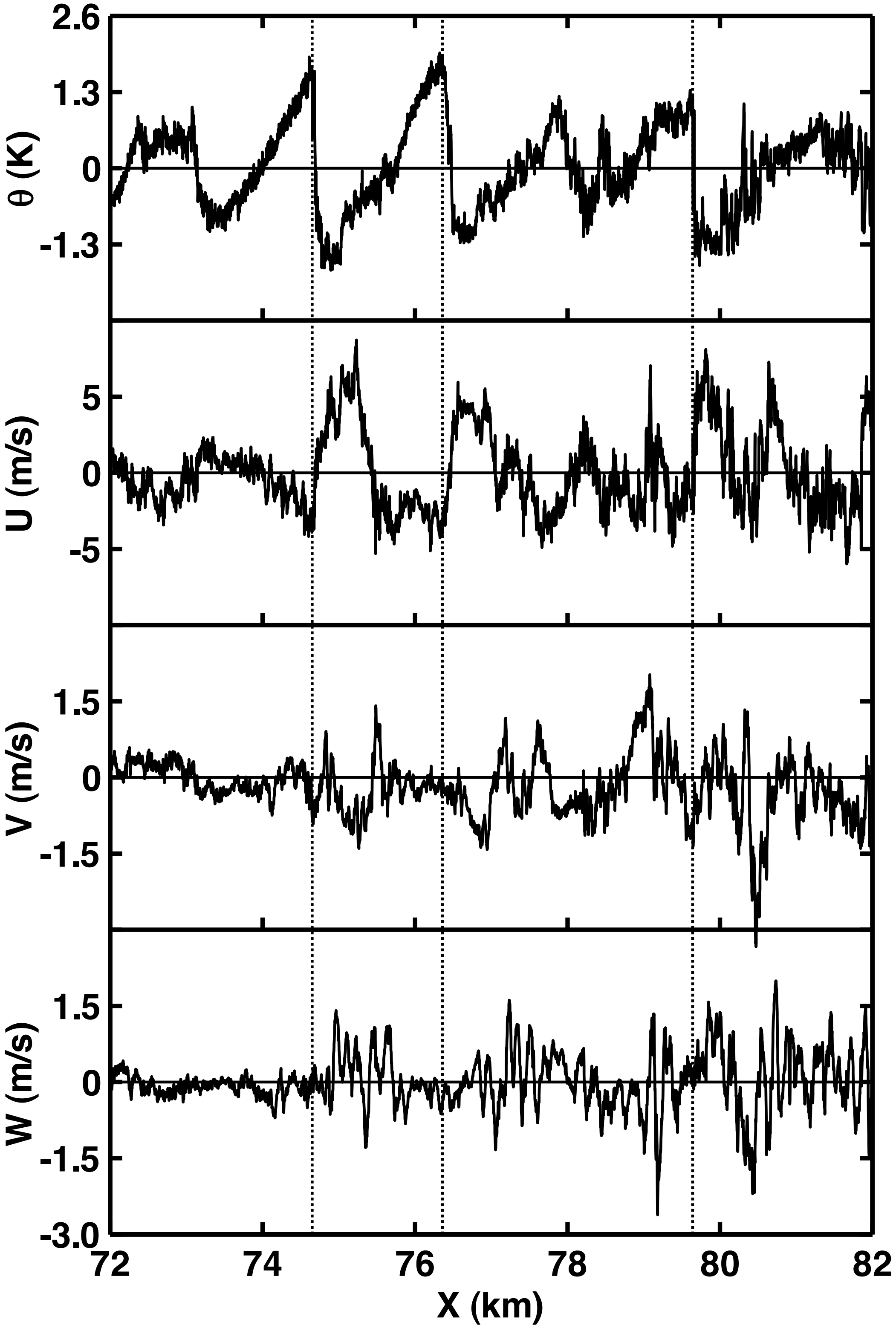


- ★ Altitude: up to 15 km
- ★ Airspeed: 100 m/s
- ★ Endurance: 8 hrs
- ★ 3 NOAA BAT probes (under wings and high on tail)
- ★ T and (U,V,W) at 50 Hz (2 m horizontal resolution)

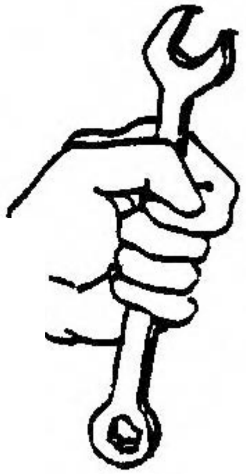
Comparison with Recent Aircraft Measurements



Simulation Results Ri=0.20



Aircraft Data (Wales)



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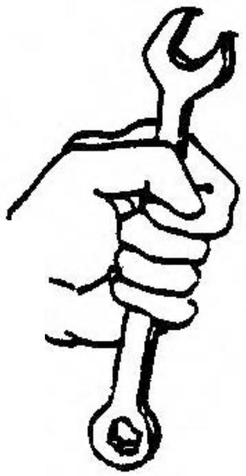
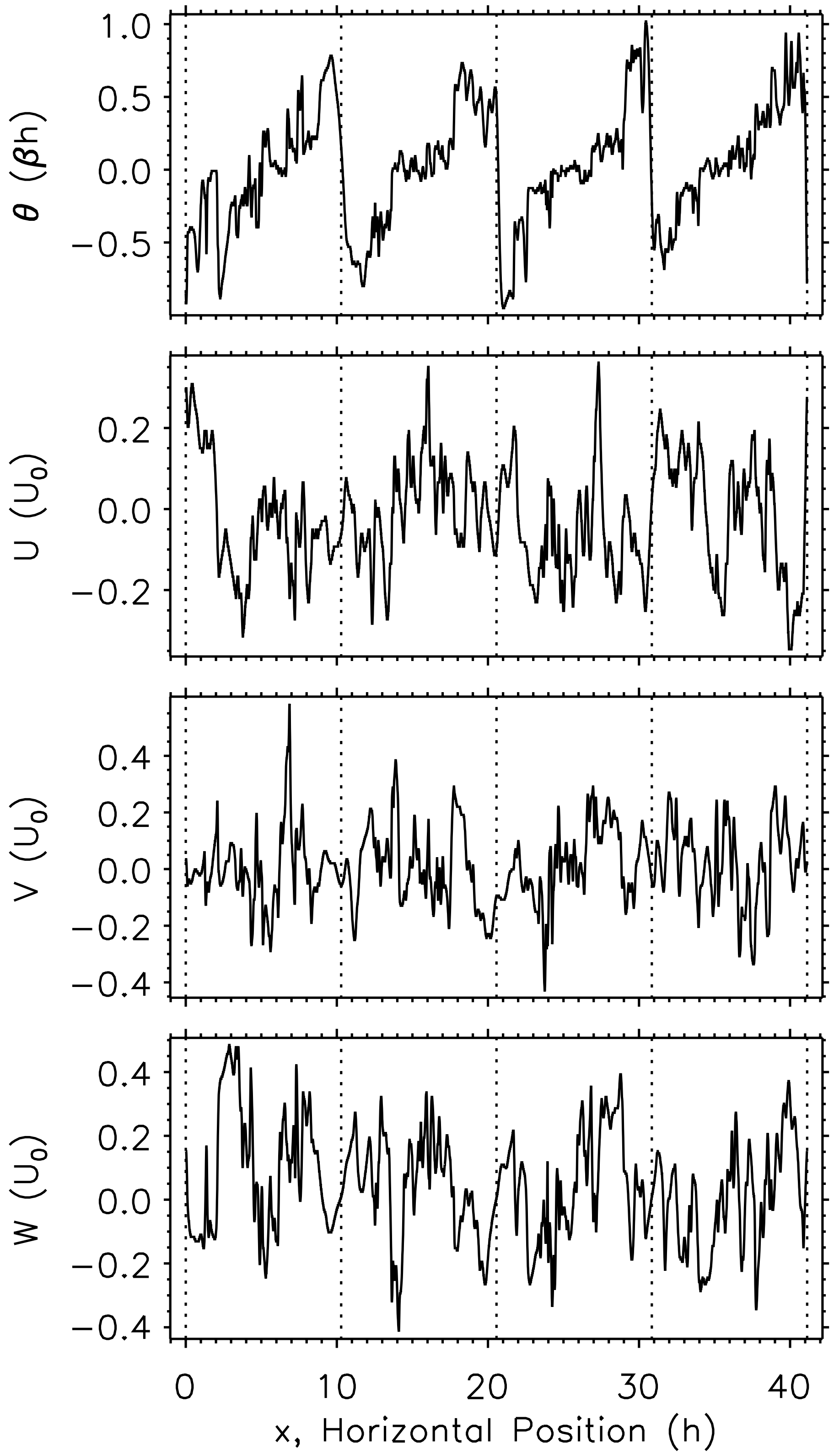
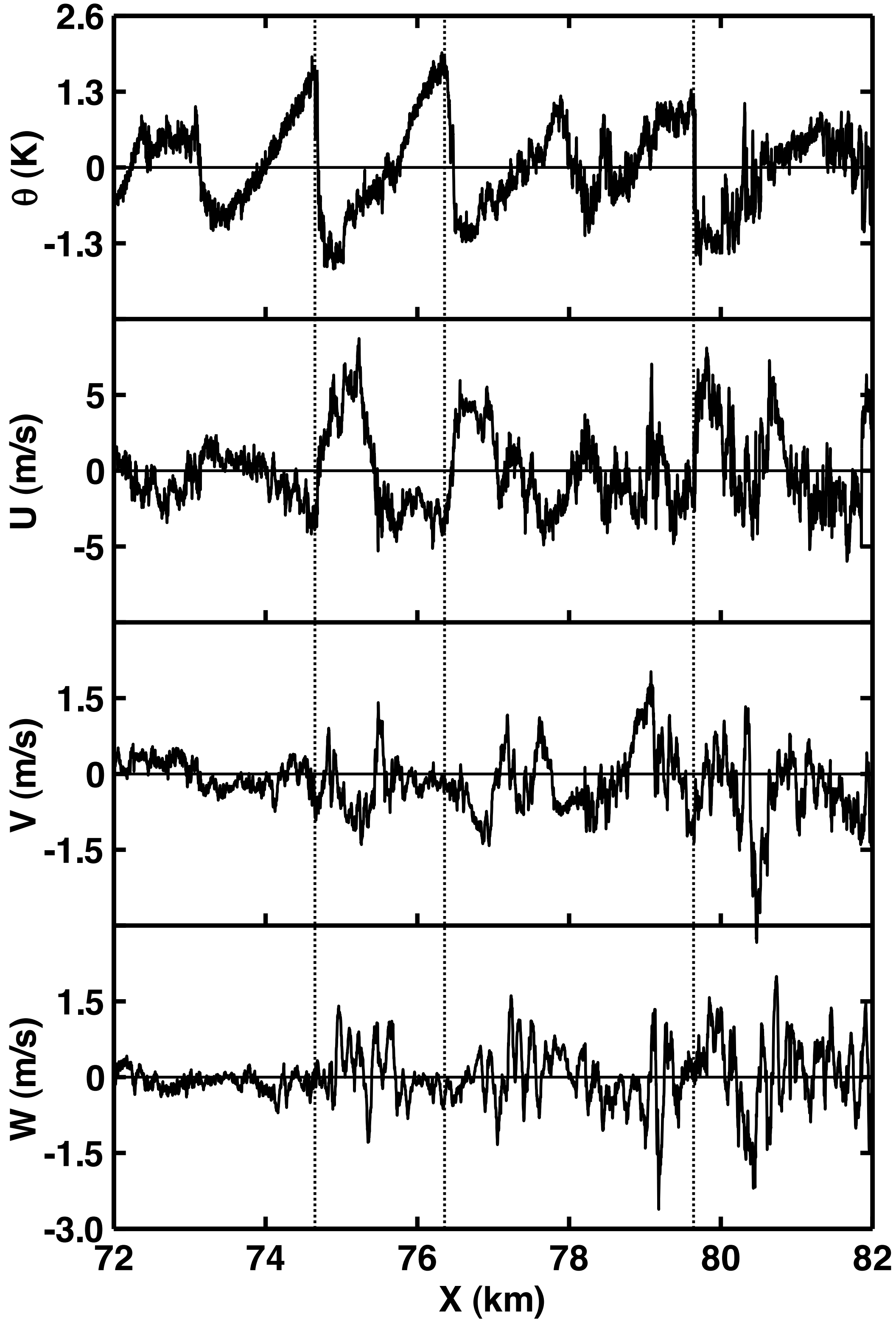
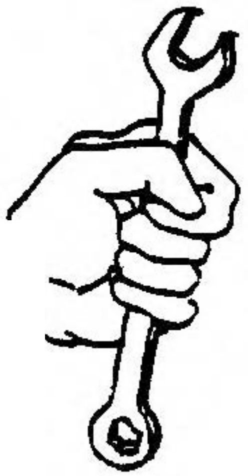


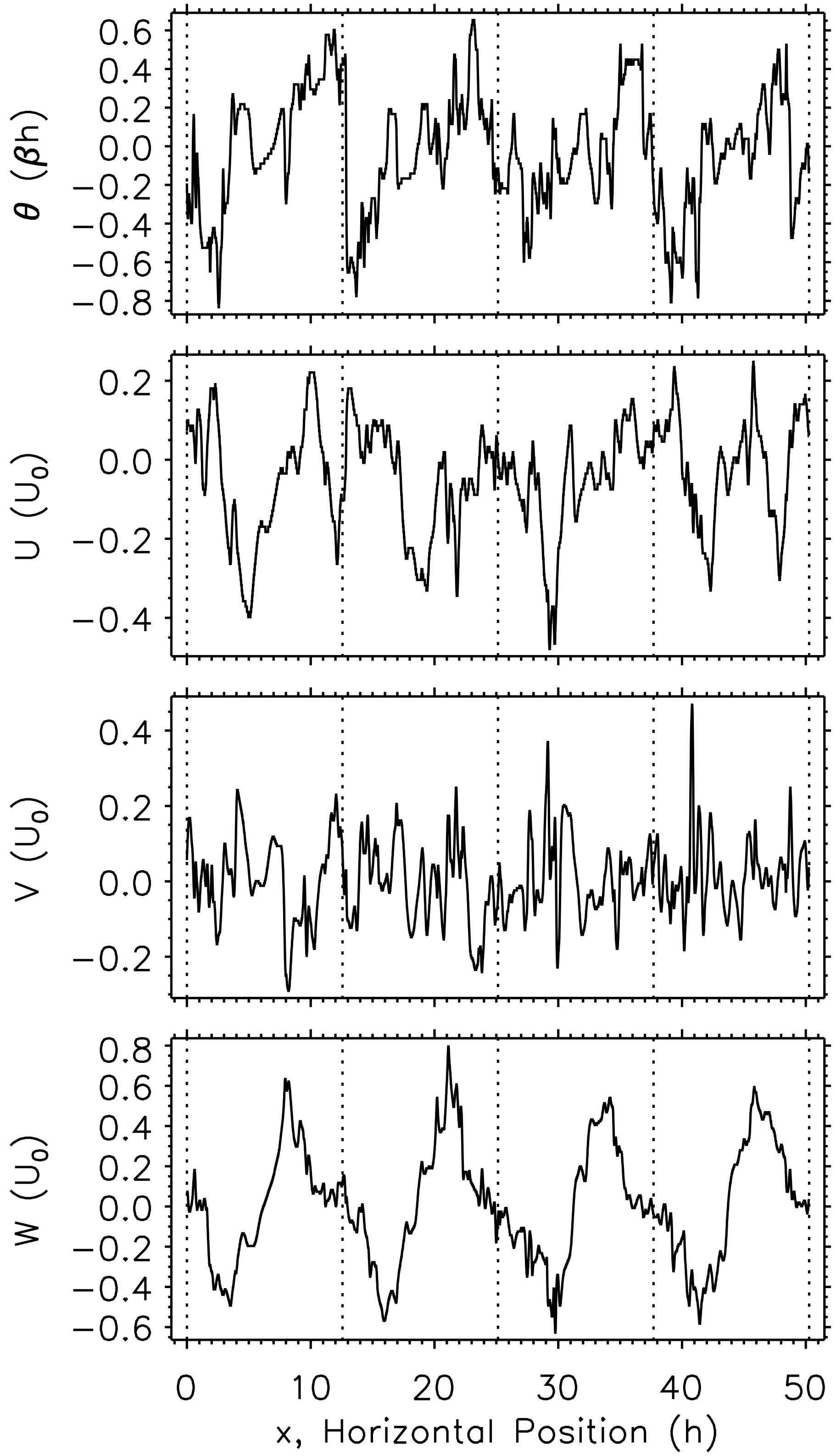

Simulation Results Ri=0.15


Aircraft Data (Wales)

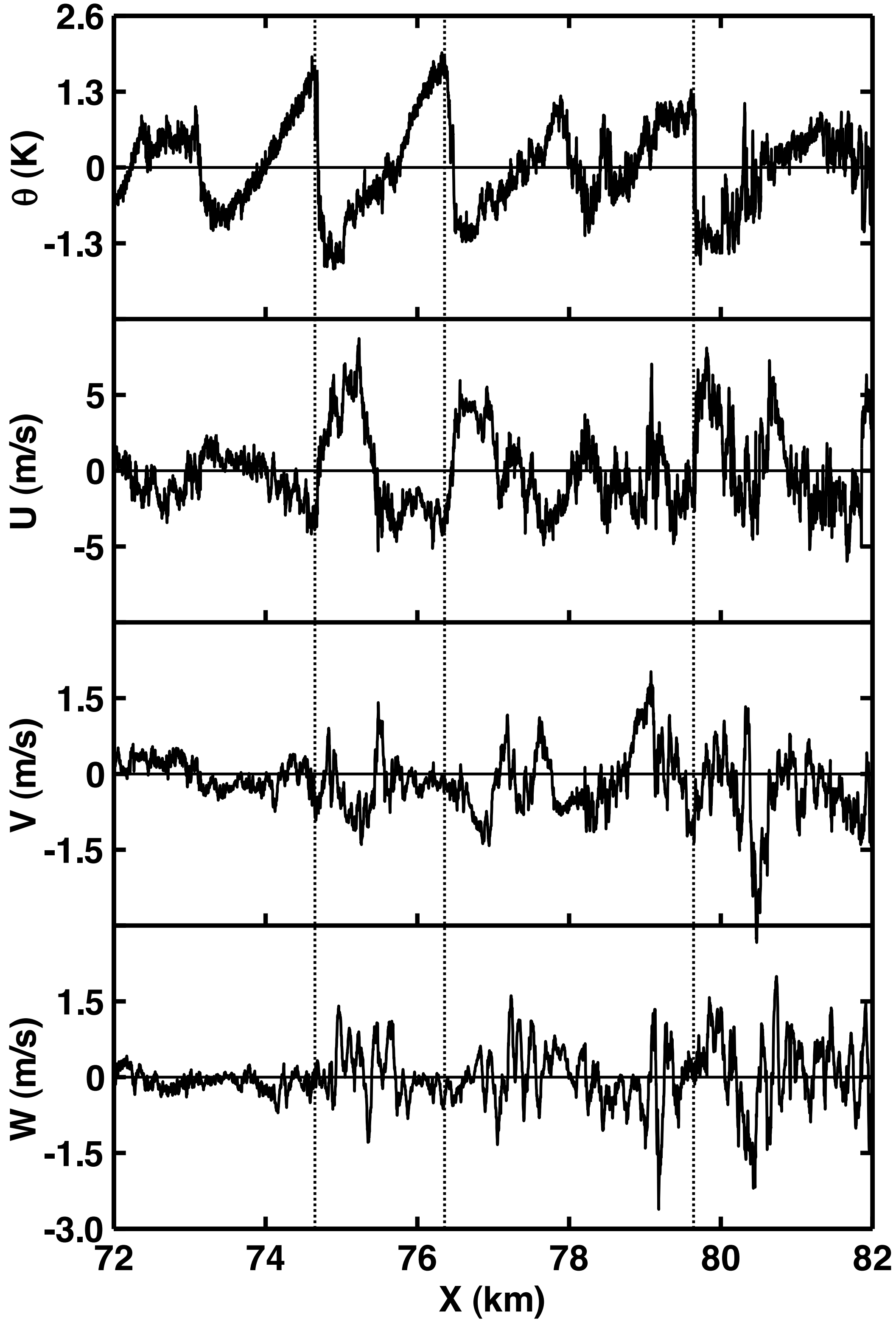
Comparison with Recent Aircraft Measurements



Simulation Results Ri=0.05

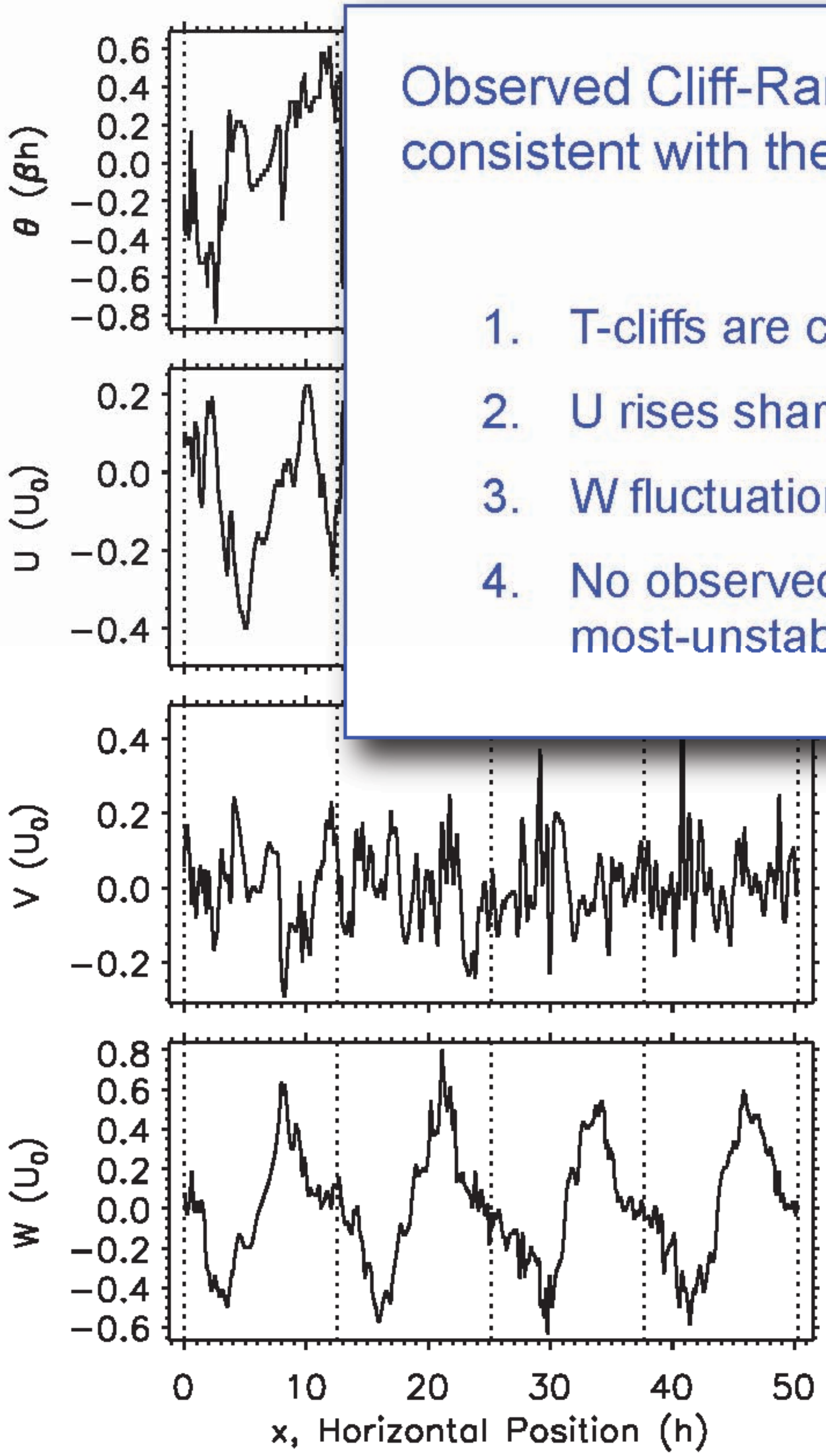


Aircraft Data (Wales)



Comparison with Recent Aircraft Measurements

Simulation Results Ri=0.05



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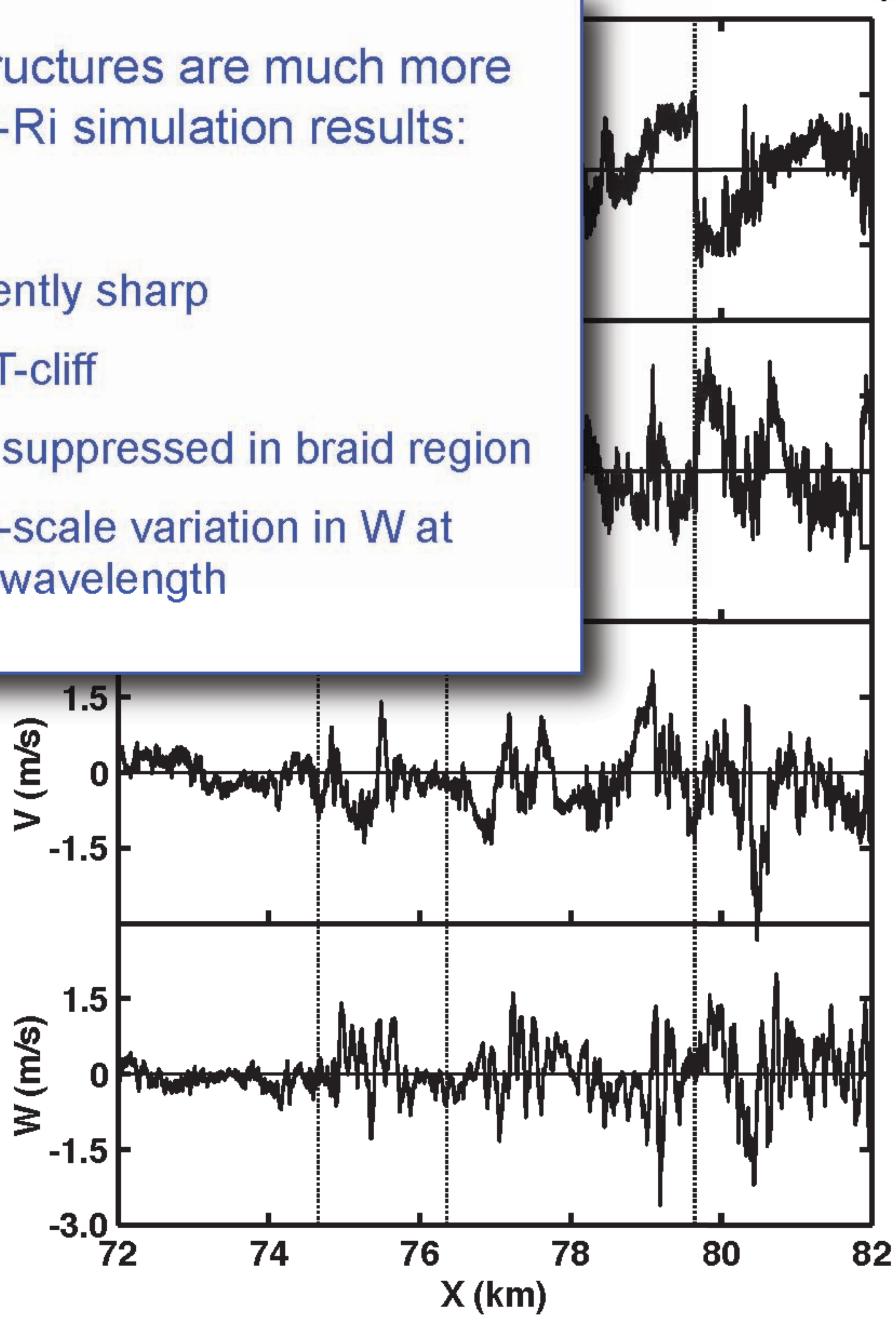
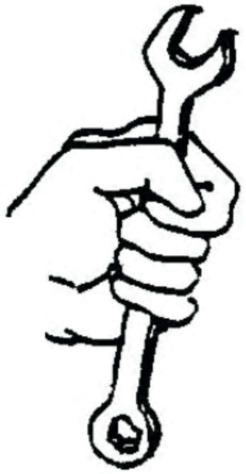
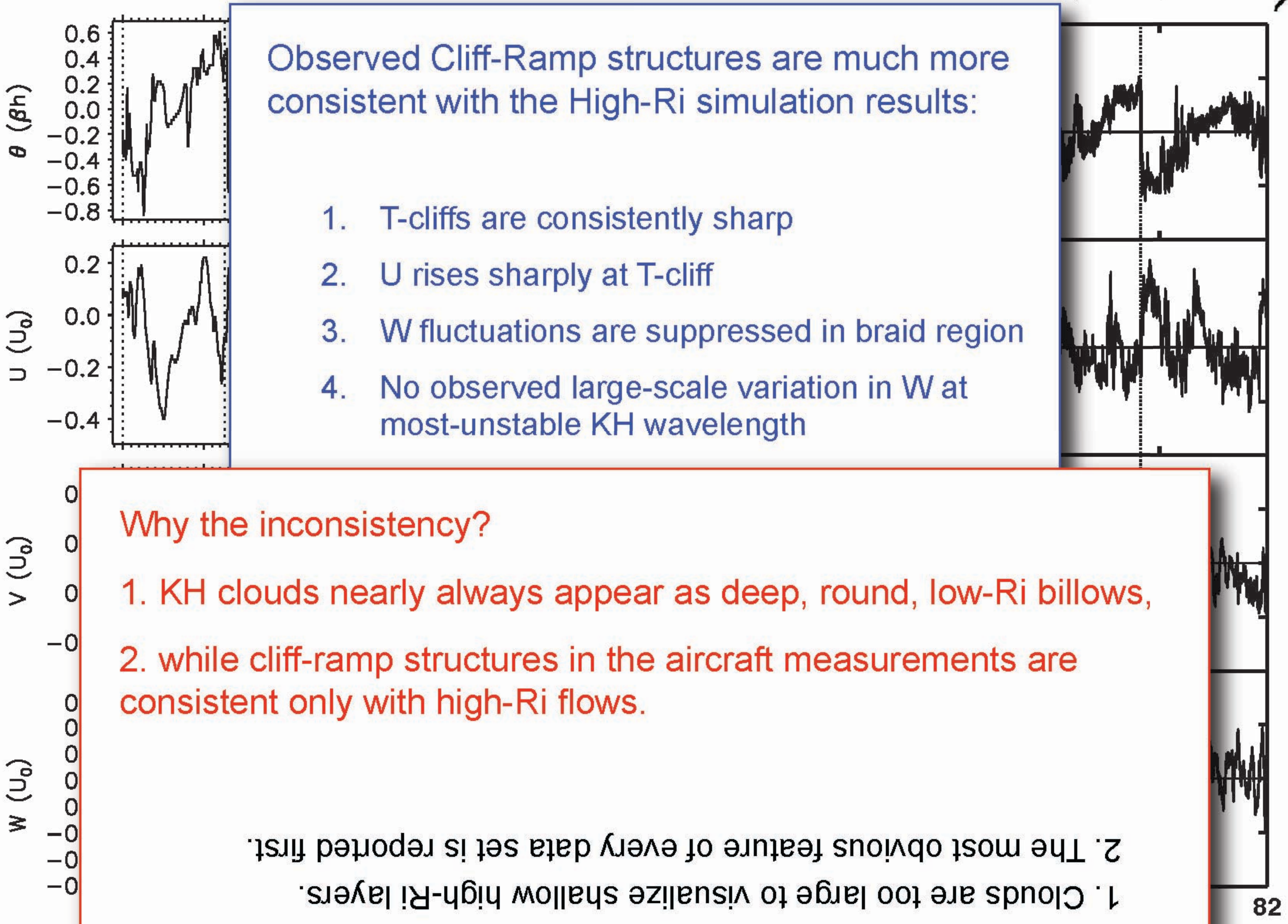




Observed Cliff-Ramp structures are much more consistent with the High-Ri simulation results:

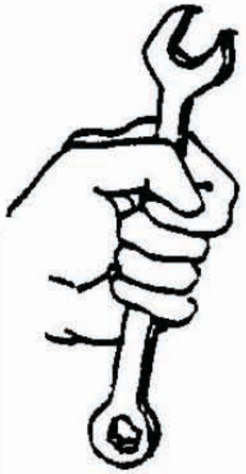
1. T-cliffs are consistently sharp
2. U rises sharply at T-cliff
3. W fluctuations are suppressed in braid region
4. No observed large-scale variation in W at most-unstable KH wavelength

Comparison with Recent Aircraft Measurements



Simulation Results Ri=0.05

Aircraft Data (Wales)



Observed Cliff-Ramp structures are much more consistent with the High-Ri simulation results:

1. T-cliffs are consistently sharp
2. U rises sharply at T-cliff
3. W fluctuations are suppressed in braid region
4. No observed large-scale variation in W at most-unstable KH wavelength

Why the inconsistency?

1. KH clouds nearly always appear as deep, round, low-Ri billows,

2. while cliff-ramp structures in the aircraft measurements are consistent only with high-Ri flows.

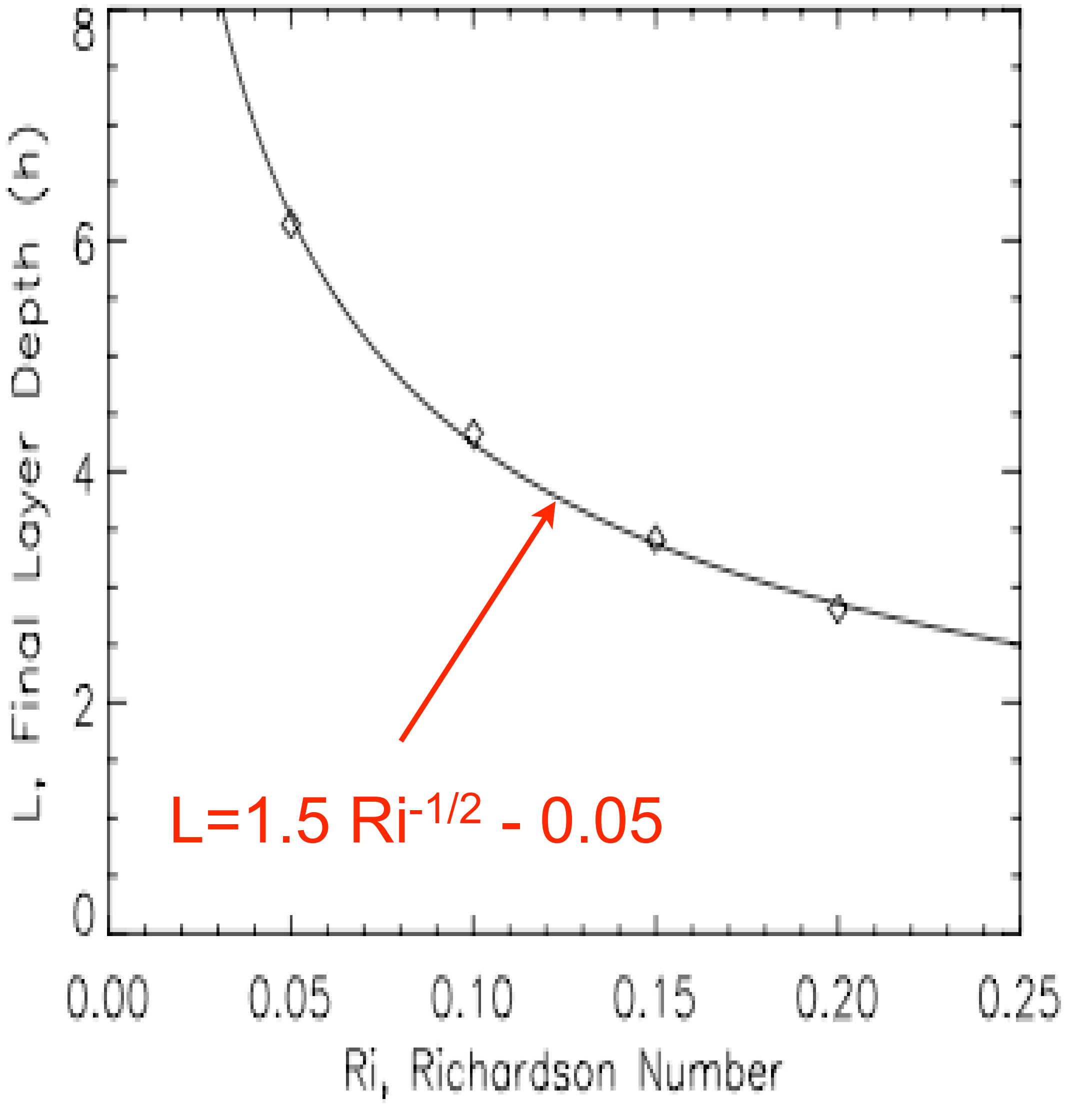
1. Clouds are too large to visualize shallow high-Ri layers.

2. The most obvious feature of every data set is reported first.

Despite dramatic differences with Ri, universal features exist.

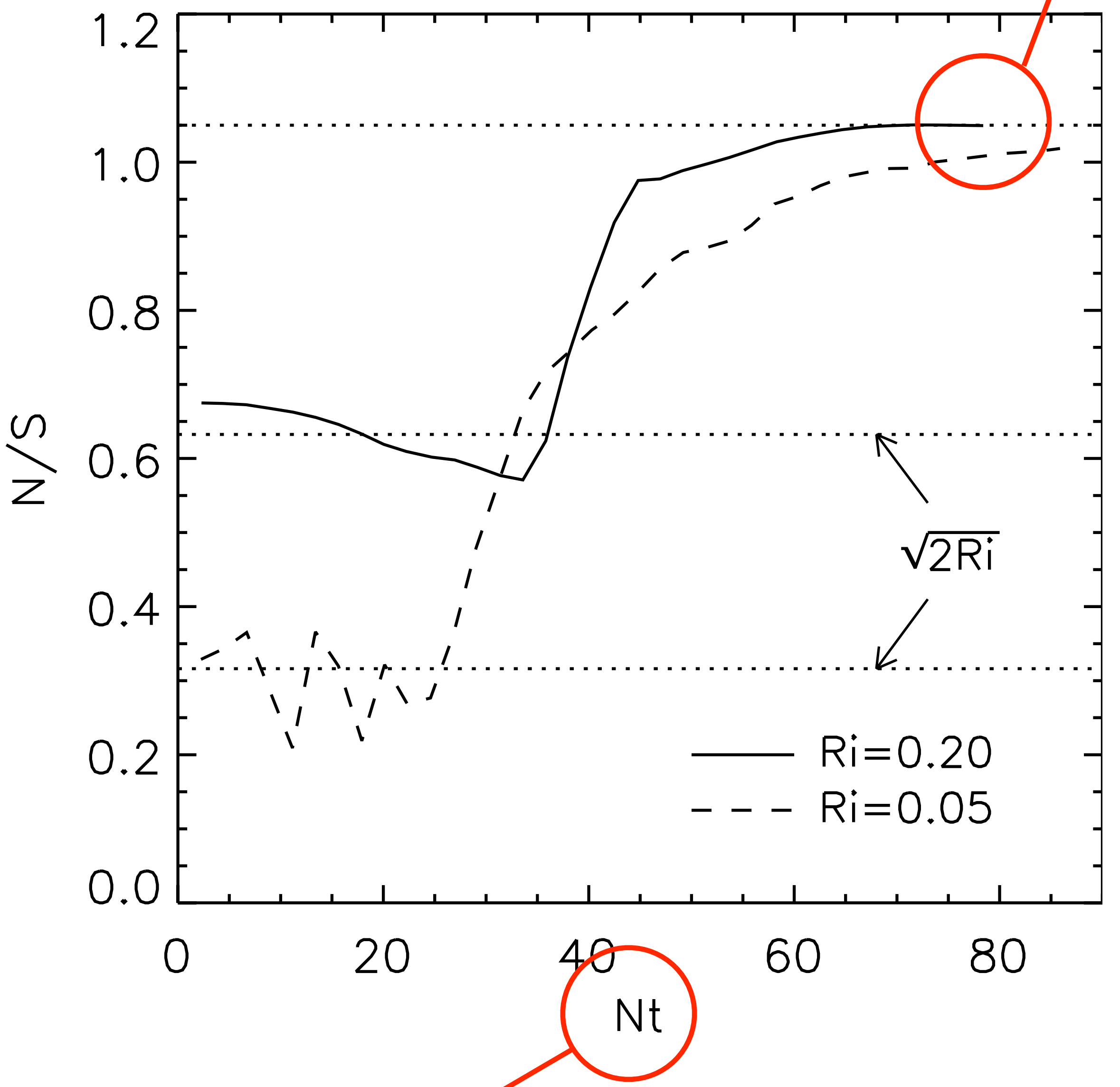
Final N/S=1.05 (Ri=0.55)

Final layer depth vs Ri



$L=1.5\ Ri^{-1/2} - 0.05$

Mid-layer N/S Evolution



time scales with $Ri^{-1/2}$

Finding our way in the *terra incognita*

Yesterday John Wyngaard described the *terra incognita* between mesoscale-model and LES-model resolutions.

- Prof. Wyngaard proposed SGS-model improvements to address this middle land for model resolution.
- Additional improvements will likely be required as well.
- Partially resolved dynamics require sophisticated SGS models that can anticipate motions in the energy-containing portion of the spectrum and represent their effects.
- Propagating waves, overturning wind-shear, and wave/mean-flow interactions at or below the model cut-off scale can be important.

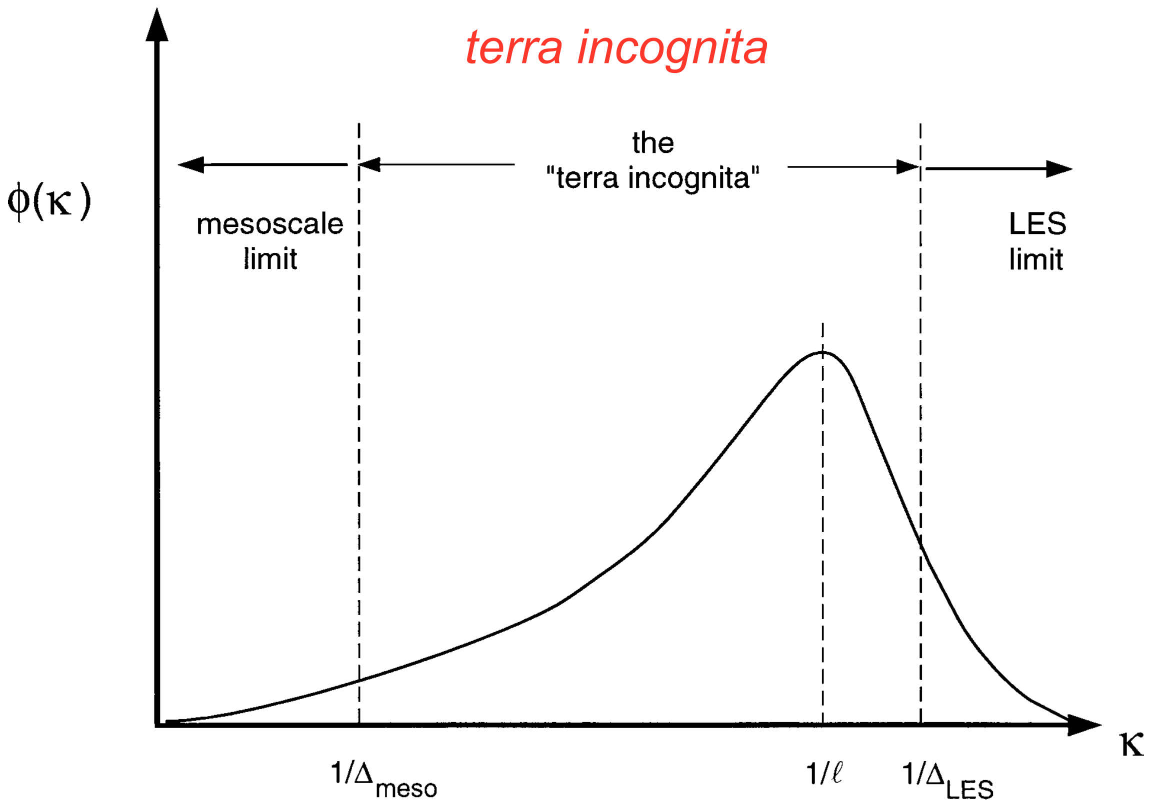


FIG. 1. A schematic of the turbulence spectrum $\phi(\kappa)$ in the horizontal plane as a function of the horizontal wavenumber magnitude κ. Its peak is at $\kappa \sim 1/l$, with l the length scale of the energetic eddies; Δ is the scale of the smoothing filter. In the mesoscale limit (left), $\Delta_{\mathrm{meso}} \gg l$ and none of the turbulence is resolved. In the LES limit (right), $\Delta_{\mathrm{LES}} \ll l$ and the energy-containing turbulence is resolved.

Finding our way in the *terra incognita*

In order to capture the effects of unresolved or partially resolved dynamics, SGS models must be knowledgeable of the dynamical motions at or near (including below) the model filter scale.

Important unresolved processes must be included in a probabilistic manner to ensure they are represented by the model.

Examples of stochastic forcing used near the cut-off length scale to include the effects of unresolved turbulent processes include:

1. The current ECMWF ensemble forecast model.
2. ‘Stochastic backscatter’ in LES studies of the atmospheric boundary layer.

To address the *terra incognita*, we are investigating using existing DNS solutions combined with observations to improve current stochastic physics and/or stochastic backscatter methods by specifying more defensible probability distributions.

Mason & Thomson, “Stochastic backscatter in LES of boundary layers.” JFM, 242, 51-78 (1992)

Westbury, Dunn & Morrison, “Analysis of a stochastic backscatter model for the LES of wall-bounded flow.” Europ. J. of Mech. B/Fluids, 23, 737-758 (2004).

Palmer et al., “Representing model uncertainty in weather and climate prediction,” Ann. Rev. Earth Planet. Sci. 33, 163-93 (2005)

Bayesian SGS Modeling

A = quantity you want to predict, e.g., $\tau_{ij},\ f_i,\ G_i,\ \Delta_{\vec{r}}T^2,\ \ldots$

F = NWP forecast variables, e.g., $T,\ P,\ U,\ V,\ W,\ \ldots$

Y_i = important unknowns, e.g., $L_i,\ \Delta U_i,\ \Delta T_i,\ Ri_i^{(o)},\ a_i,\ Re_i,\ z_i,\ \ldots$

atmospheric turbulence patch parameters (layer depth, velocity and temperature jump, local Richardson number, age, Reynolds number, altitude, ...)

prediction takes form of a joint probability distribution:

$$[\,A\,,\,F\,] = \int [\,A\,,\,F\,,\,Y\,]\,dY$$

where Y represents a collection of layers: $[\,Y\,] = [\,Y_1\,,\,Y_2\,,\,\ldots\,,\,Y_N\,]$

notation:

[a] - probability of ‘a’

[a , b] - joint probability of ‘a’ and ‘b’

[a | b] - conditional probability of ‘a’ given ‘b’

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F = NWP forecast variables, e.g., $T,\ P,\ U,\ V,\ W,\ \ldots$

Y_i = impo

atmosp
jump, l

predicti

where Y

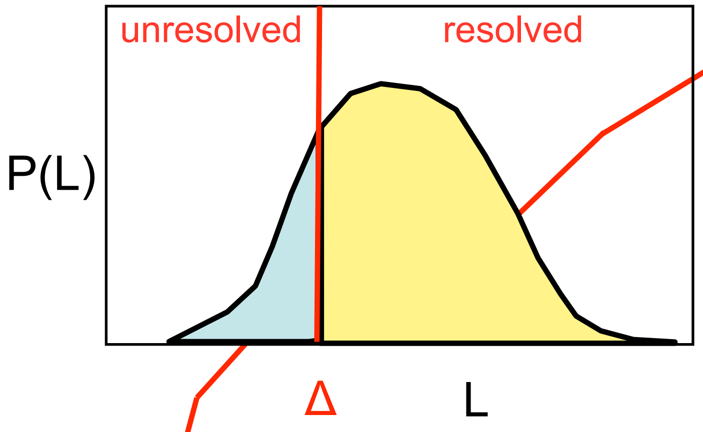
Advantages

1. Permits inclusion of measurement results directly.
2. Produces model uncertainty estimates naturally.
3. Relieves SGS model of convenient mathematical assumptions (e.g., universal turbulence range, mixing length model, eddy viscosity, etc.).
4. Allows incorporation of complex physics, even if not completely understood.

[a] - probability of ‘a’
[a , b] - joint probability of ‘a’ and ‘b’
[a | b] - conditional probability of ‘a’ given ‘b’

Bayesian SGS Modeling

Some layers Y will be resolved and some will have to be modeled. Therefore, we split the integral at $L_i = \Delta$, where Δ is the NWP model cut-off length scale.



Turbulence climatology and/ or real-time observations

Estimate with ensemble runs or knowledge of F uncertainty

$$[\,A\,,\,F\,] = \int_0^\Delta [\,A\,|\,F\,,\,Y\,]\,[\,F\,|\,Y\,]\,[\,Y\,]\,dY + \int_\Delta^\infty [\,A\,|\,F\,,\,Y\,]\,[\,Y\,|\,F\,]\,[\,F\,]\,dY$$

Filtered climatology realizations

resolved by NWP or secondary model

Determined predominantly by F or Y subject to A's sensitivity to large- or small-scale processes.

Bayesian SGS Modeling

Turbulence climatology and/
or real-time observations

$$[\,A\,,\,F\,] = \int_0^{\Delta} [\,A \mid F\,,\,Y\,]\,[\,F \mid Y\,]\,[\,Y\,]\,dY + \int_{\Delta}^{\infty} [\,A \mid F\,,\,Y\,]\,[\,Y \mid F\,]\,[\,F\,]\,dY$$

Filtered climatology realizations

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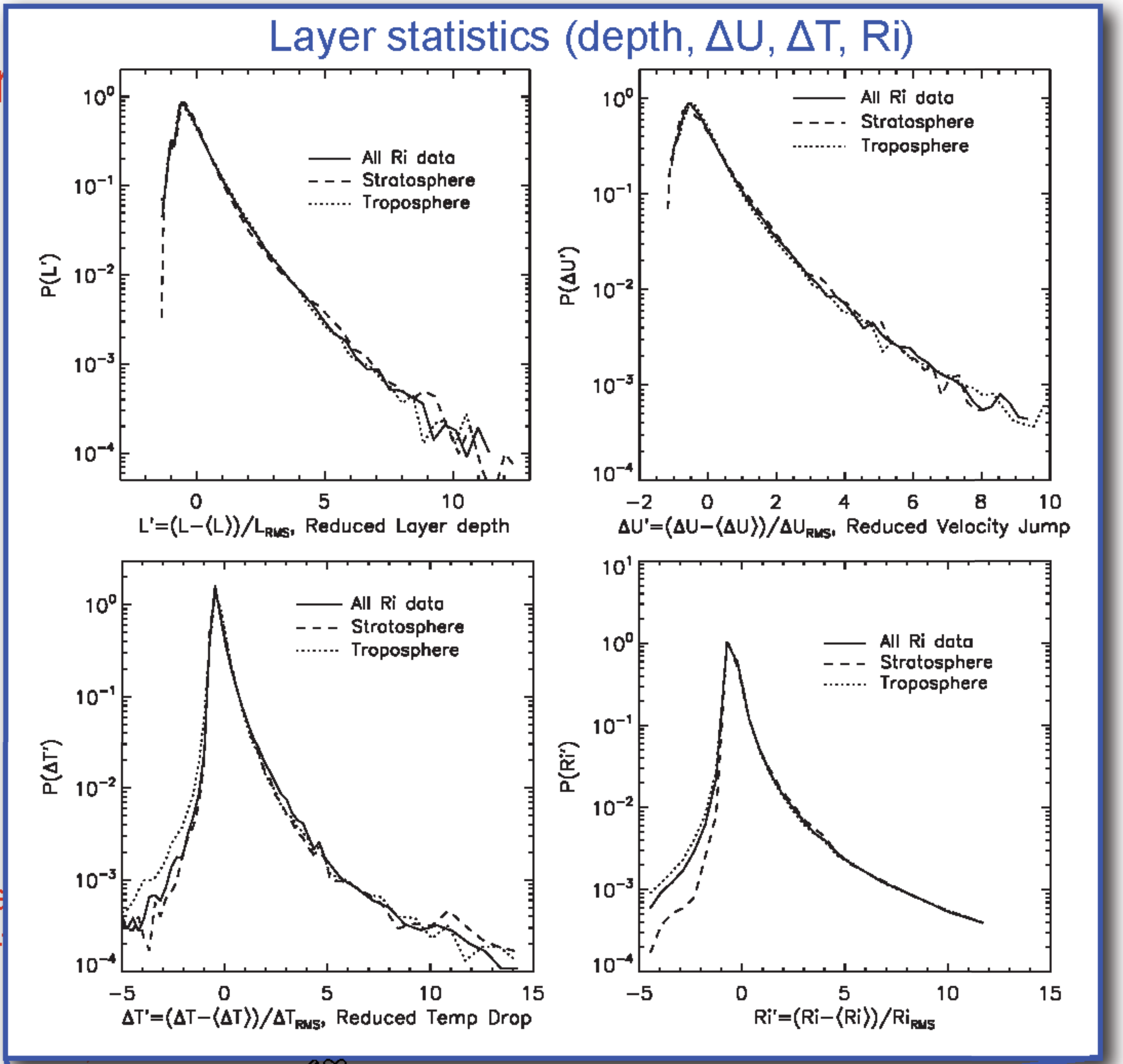
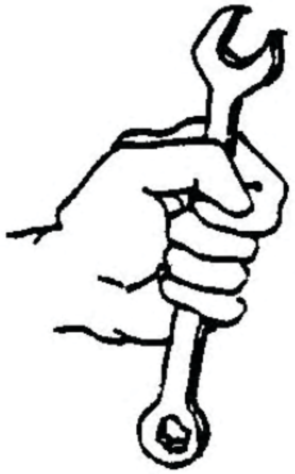
Bayesian



Layer statistics (depth, ΔU, ΔT, Ri)

Turbule

or real-



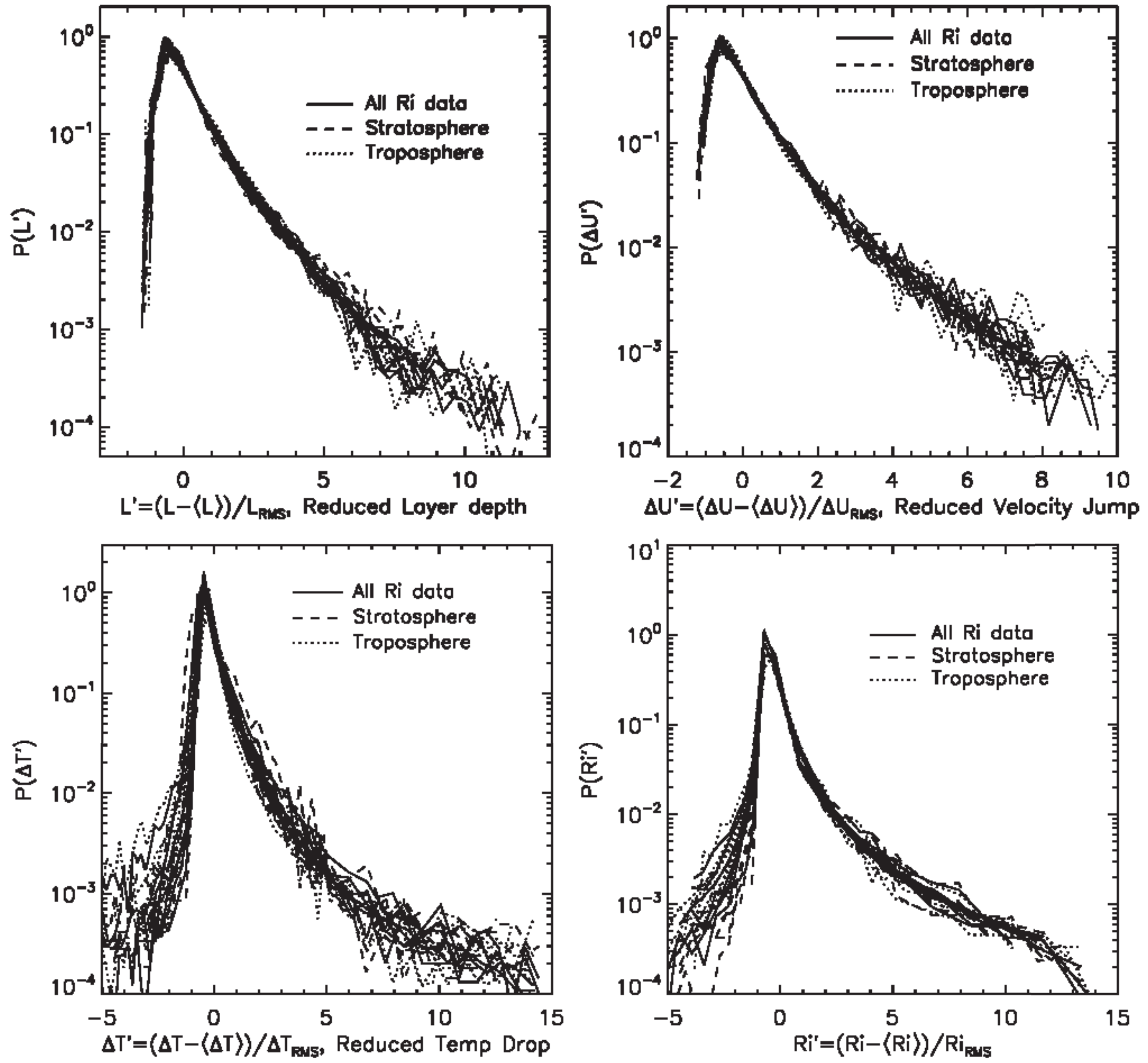
$$[A, F] = \int_0^\Delta [A \mid F, Y]\,[F \mid Y]\,[Y]\,dY + \int_\Delta^\infty [A \mid F, Y]\,[Y \mid F]\,[F]\,dY$$

Filtered climatology realizations

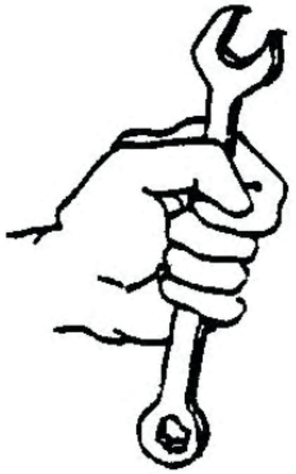
Determined predominantly by F or Y subject to A's sensitivity to large- or small-scale processes.

Bayesian

Layer statistics (depth, ΔU, ΔT, Ri)



Layer PDFs assume well-defined universal shapes, independent of location.



Turbule
or real-

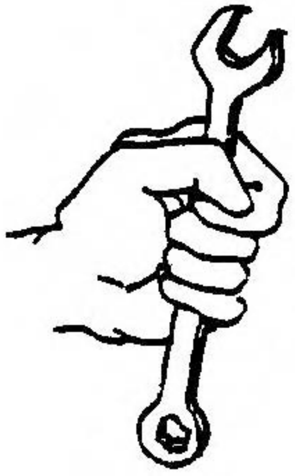
$$[A,F] = \int_0^\Delta [A|F,Y][F|Y][Y]\,dY + \int_\Delta^\infty [A|F,Y][Y|F][F]\,dY$$

Filtered climatology realizations

Determined predominantly by F or Y subject to A's sensitivity to large- or small-scale processes.

Bayesian SGS Modeling

Turbulence climatology and/
or real-time observations



$$[A\,,\,F] = \int_0^{\Delta} [A \,|\, F\,,\,Y]\,[F \,|\, Y]\,[Y]\,dY + \int_{\Delta}^{\infty} [A \,|\, F\,,\,Y]\,[Y \,|\, F]\,[F]\,dY$$

Filtered climatology realizations

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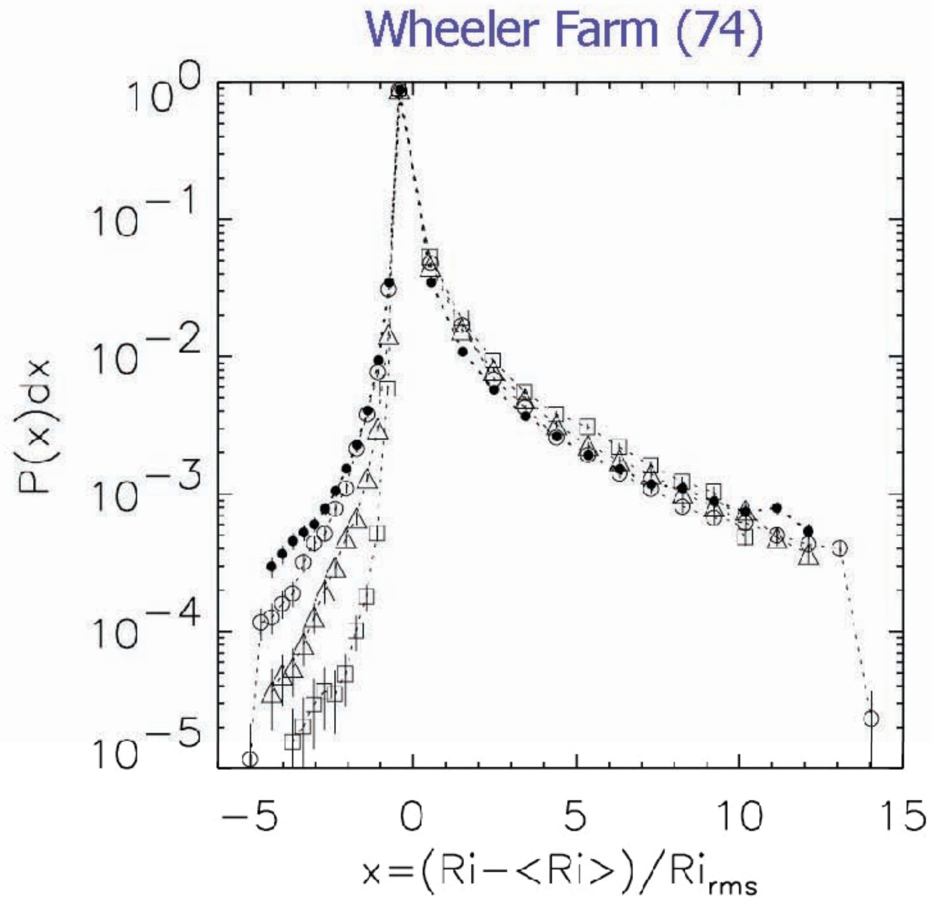
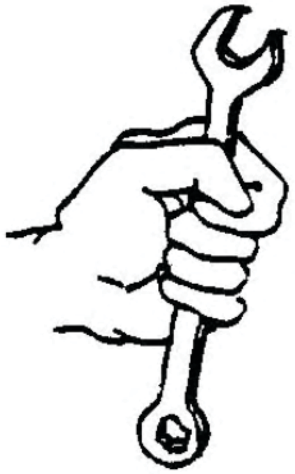
Bayesian S





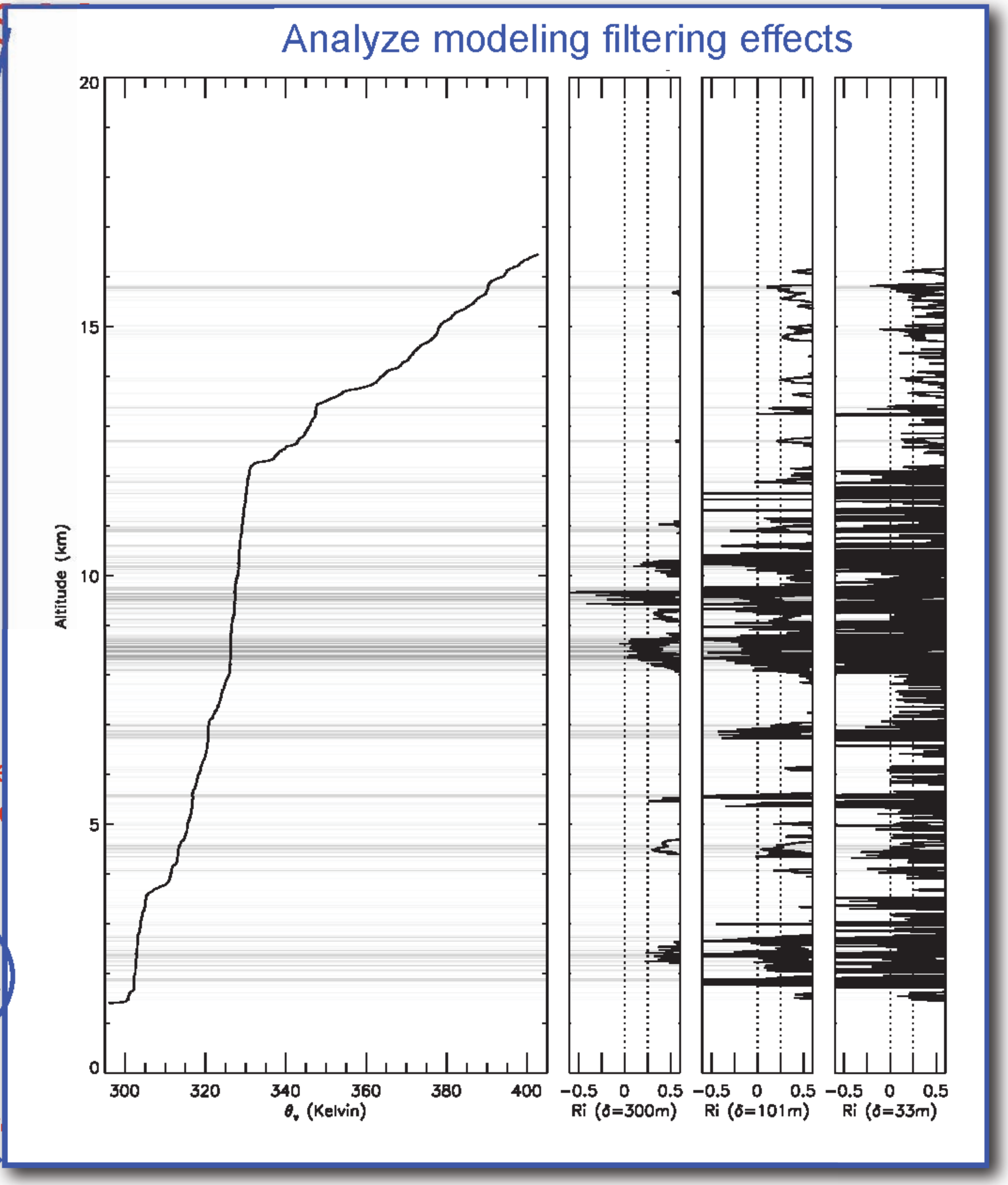
$$[A, F] = \int_0^\Delta [A \mid F, Y]\,[F \mid Y]\,[$$

Turbulence
or real-tim

Filtered climatology r

Determined predominantly by F or Y subject to A's sensitivity to large- or small-scale processes.

Analyze modeling filtering effects

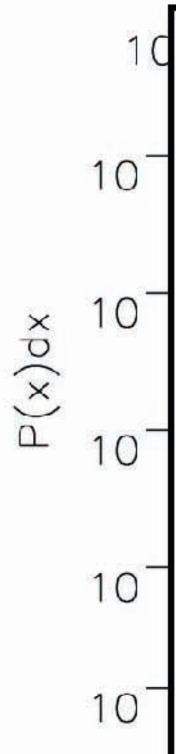


$$Ri = \frac{g\,\alpha\,\partial_z T}{(\partial_z U)^2}$$

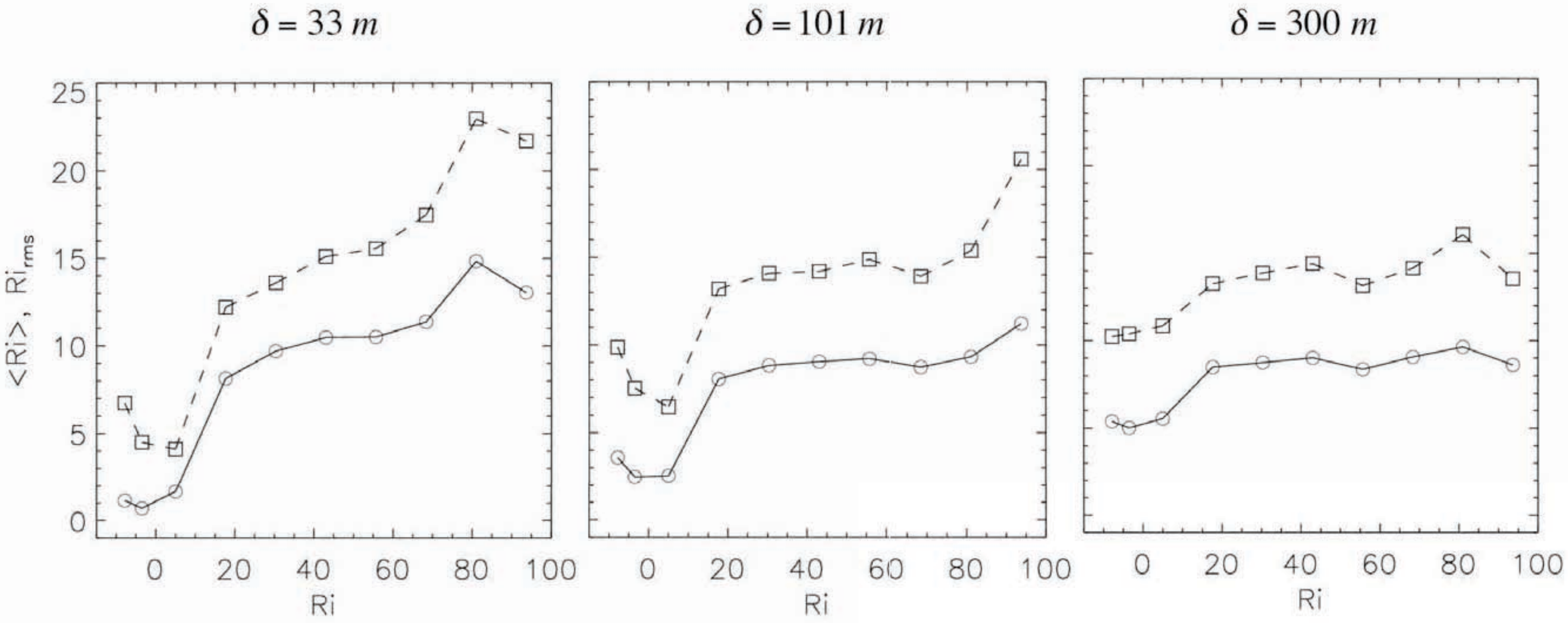
Bayesian S

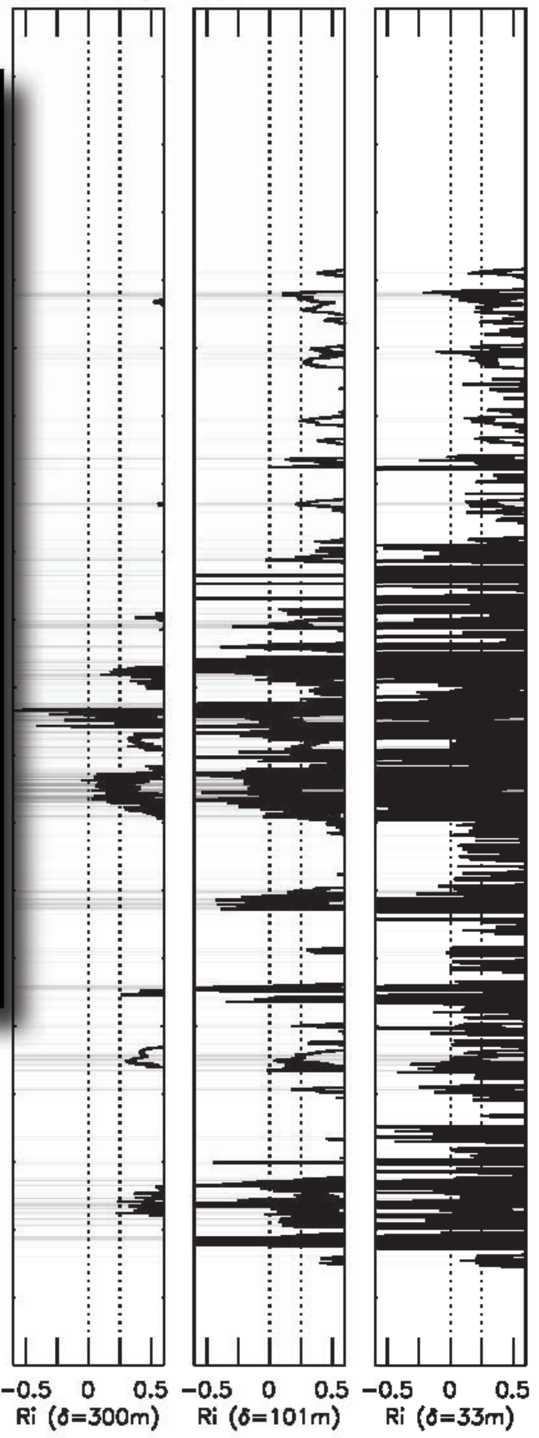
Analyze modeling filtering effects

Wheeler Farm (74)



Conditional PDFs and Model Filtering Effects





or real-tim

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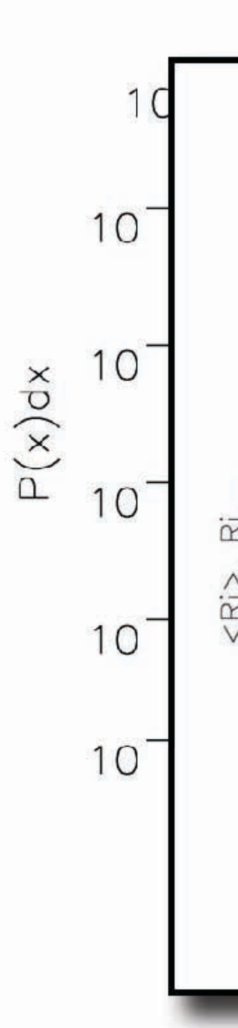

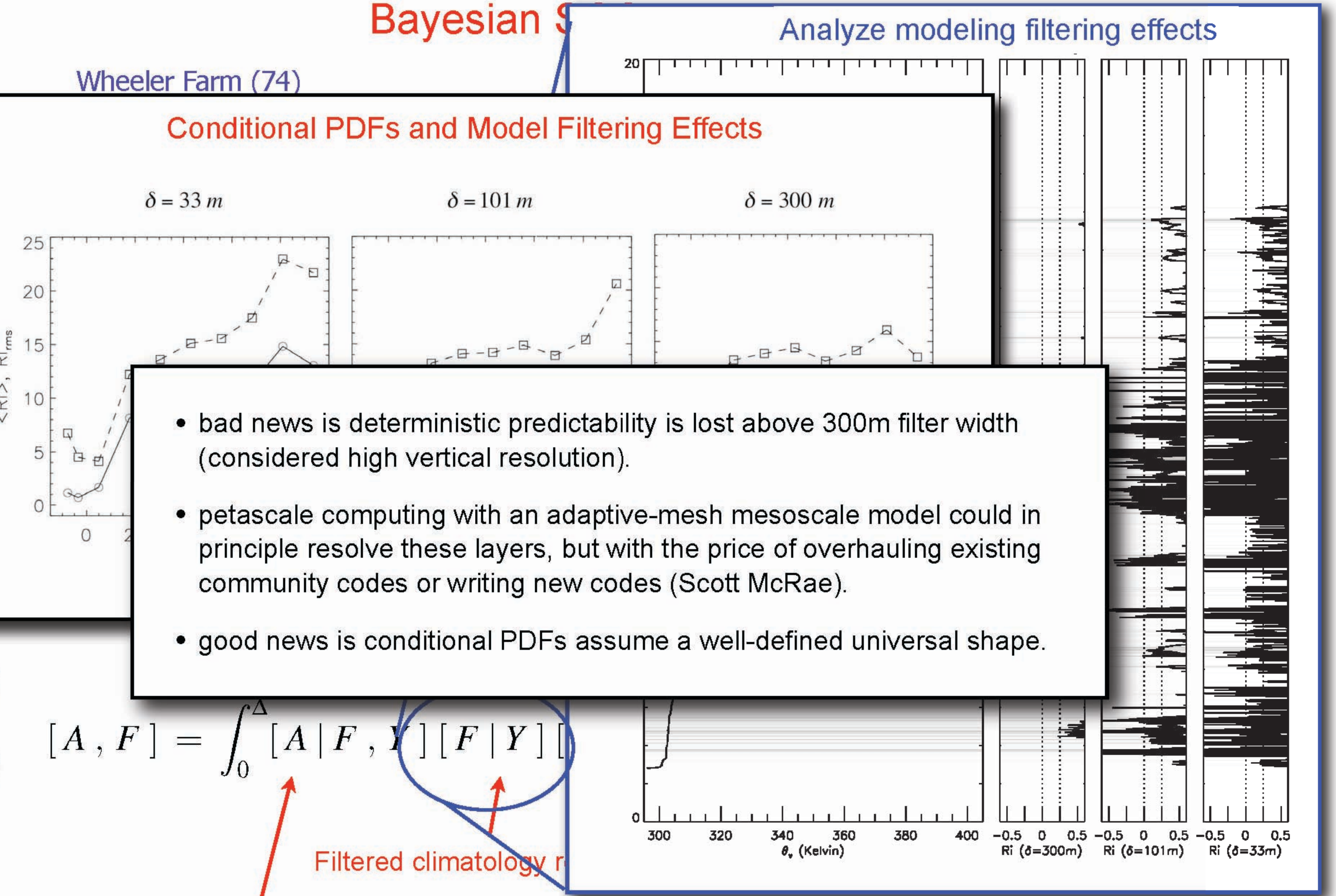

Analyze modeling filtering effects

Conditional PDFs and Model Filtering Effects

- bad news is deterministic predictability is lost above 300m filter width (considered high vertical resolution).
- petascale computing with an adaptive-mesh mesoscale model could in principle resolve these layers, but with the price of overhauling existing community codes or writing new codes (Scott McRae).
- good news is conditional PDFs assume a well-defined universal shape.

$$[A , F] = \int_0^{\Delta} [A \mid F , Y] [F \mid Y] [$$

Filtered climatology r

Determined predominantly by F or Y subject to A's sensitivity to large- or small-scale processes.

$$Ri = \frac{g\,\alpha\,\partial_z T}{(\partial_z U)^2}$$

Bayesian SGS Modeling

Turbulence climatology and/
or real-time observations

$$[\,A\,,\,F\,] = \int_0^{\Delta} [\,A\,|\,F\,,\,Y\,]\,[\,F\,|\,Y\,]\,[\,Y\,]\,dY + \int_{\Delta}^{\infty} [\,A\,|\,F\,,\,Y\,]\,[\,Y\,|\,F\,]\,[\,F\,]\,dY$$

Filtered climatology realizations

Determined predominantly by F or Y subject
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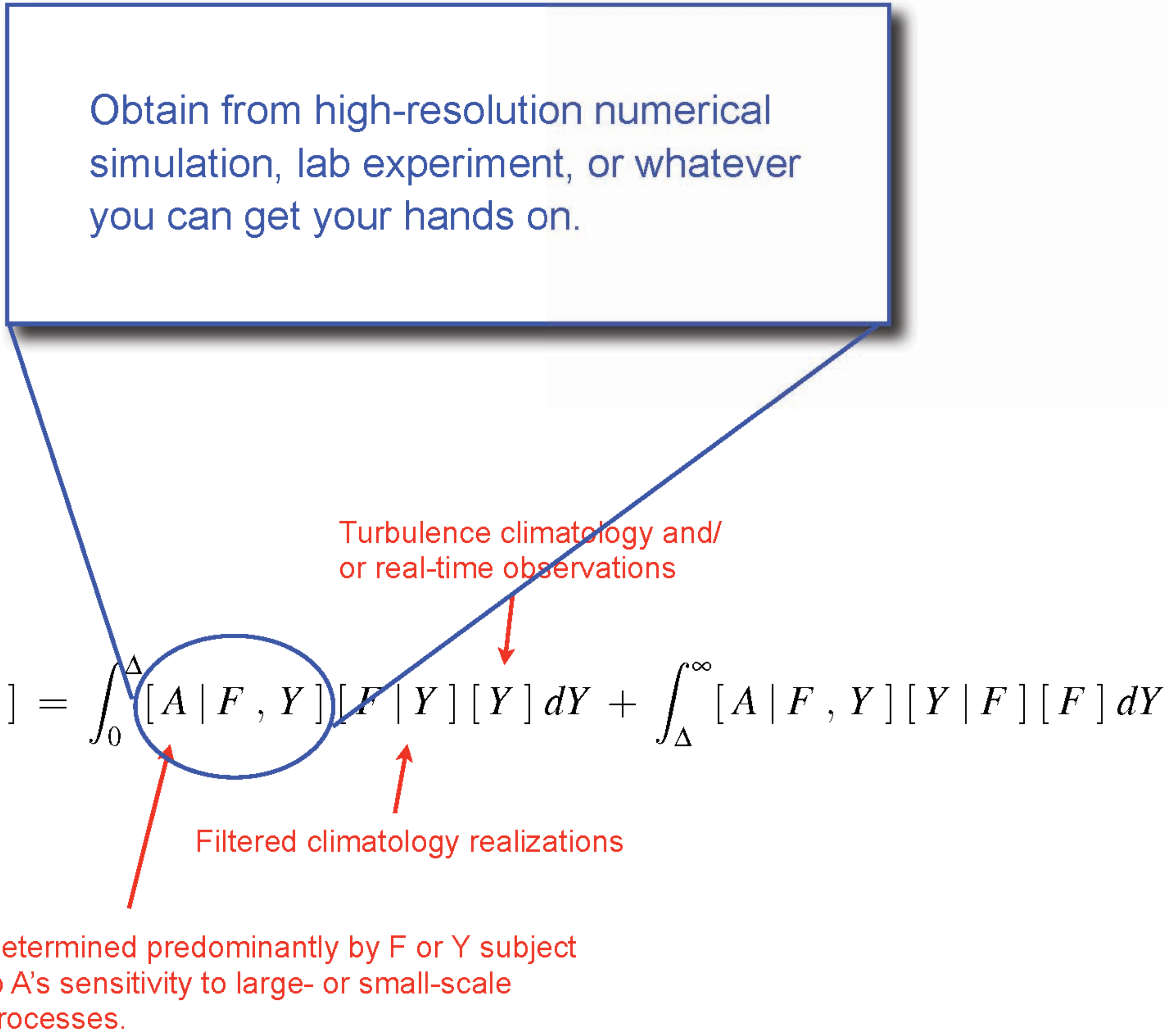
processes.

Bayesian SGS Modeling



Obtain from high-resolution numerical simulation, lab experiment, or whatever you can get your hands on.

Turbulence climatology and/ or real-time observations

$$[A\,,F\,] = \int_0^{\Delta} [A\,|\,F\,,Y\,]\,[F\,|\,Y\,]\,[Y\,]\,dY + \int_{\Delta}^{\infty} [A\,|\,F\,,Y\,]\,[Y\,|\,F\,]\,[F\,]\,dY$$

Filtered climatology realizations

Determined predominantly by F or Y subject to A's sensitivity to large- or small-scale processes.

Conclusions

1. Shear and gravity-wave dynamics produce layered turbulence that is episodic in time.

2. The unresolved dynamics are important and their likelihood of occurrence must be modeled.

3. Measurements demonstrate infrequent but significant deep CAT events and numerous less important shallow CAT events that produce near-universal PDFs that can be characterized by two parameters (mean and variance).

4. DNS results for turbulent shear have been validated with balloon, radar, and aircraft data, and clear deviations from isotropic theory are seen for both the DNS and the observations.

5. Different morphology and evolution exists for weakly and strongly stratified events, permitting identification of the initial Ri in aircraft data.

6. Gravity-wave-breaking simulations demonstrate amplitude reductions from 1.1 to 0.3, far in excess of conventional linear saturation theory. Expect different degree of amplitude reduction for different frequency waves.

7. We have defined a Bayesian framework for probabilistic SGS formulations.

Ongoing Work

1. Constructing atmospheric Ri census via refined simulation/aircraft-data comparisons.

2. Developing needed BHM conditional PDFs from DNS results.